Numerical Stress Analysis of Sandwich Cryogenic Pipeline

by

Faza Muhammad Billah

14690

Dissertation submitted in partial fulfilment of

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Bandar Seri Iskandar

31750 Tronoh

Perak Darul Ridzuan

Malaysia

CERTIFICATION OF APPROVAL

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Approved by,

____

(Dr Zahiraniza Mustaffa)

UNIVERSITI TEKNOLOGI PETRONAS

TRONOH, PERAK

Sept 2014

CERTIFCATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

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FAZA MUHAMMAD BILLAH

ABSTRACT

Liquefied natural gas (LNG) pipeline is often built on top of trestle system to transport it from liquefaction plant to LNG vessel. However, the use a vessel is very expensive for long term operation, which led to the development of subsea sandwich cryogenic pipeline. Although the new pipeline can resist the cryogenic temperature, its performance in terms of strength is yet to be tested under deep water situation. Therefore, this research aim to determine the strength of the sandwich cryogenic pipeline in terms of stress, strain, deformation, safety factor, and heat flux using ANSYS as finite element modelling software. The results were compared using three different materials, which are stainless steel, 36% nickel (Invar), and the proposed 29% nickel (Kovar). The results showed that, in term of overall performance, Kovar performed better in terms of stress, strain, deformation, and safety factor. However, in terms of heat flux, Invar performed better than Kovar. To improve the reliability of this research, further modification is suggested by conducting fatigue and stability test in the analysis.

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Table of Contents

CERTIFICATION OF APPROVAL ii

CERTIFCATION OF ORIGINALITY iii

ABSTRACT iv

ACKNOWLEDGEMENTS v

List of Figures viii

List of Tables ix

CHAPTER 1: 1

INTRODUCTION 1

1.1 Project Background 1

1.2 Problem Statement 2

1.3 Scope of Study and Objectives 3

CHAPTER 2: 4

LITERATURE REVIEW 4

2.1 Carbon Steel 4

2.1.1 Basic Carbon Steel Design 4

2.1.2 Material Properties 5

2.1.3 Pipe Fabrication 6

2.2 Low Expansion Nickel Alloy 6

2.3 Pipe-In-Pipe-In-Pipe (PiPiP) Pipeline 7

2.3.1 Pipe-in-Pipe-in-Pipe (PiPiP) Design Concept 7

2.3.2 Pipeline Configuration 8

2.3.3 Existing Cryogenic Pipeline 9

2.4 Problems of Cryogenic Pipeline 10

2.4.1 Contraction Problem 10

2.4.2 Thermal Performance 12

2.5 Finite Element Modelling 13

2.6 Experimental Test on Pipe-in-Pipe System 15

CHAPTER 3: 17

METHODOLOGY 17

3.1 Research Methodology 17

3.2 Pipeline Design 20

3.3 Design Data 20

3.3.1 Production Profiles 20

3.4 Diameter and Wall Thickness 21
3.4.1 Piping Codes 21
3.4.2 Design Procedure..................21
3.5 Pipeline Stresses and Load Identification 23
3.6 Cryogenic Pipeline Modelling using Finite Element Modelling (FEM) 23
3.6.1. Pipe Model Properties..................23
3.6.2 Mechanical Property of Pipe Material 24
3.6.3 Analysis System 25
3.6.4 Modelling 25
3.6.5 Meshing..................26
3.6.6 Defining Loads 26
3.6.7 Solution 28
CHAPTER 4:..................30
RESULT AND ANALYSIS 30
4.1 Calculated Wall Thickness..................30
4.1.1 ANSI/ASME B31.3 Standard 30
4.1.2 ANSI/ASME B31.4 Standard 30
4.2 Simulated Stainless Steel 304L Pipeline..................31
4.3 Simulated 29% Nickel (Kovar) Pipeline..................32
4.4 Simulated 36% Nickel (Invar) Pipeline. 34
4.5 Discussion 36
4.5.1 Wall thickness 36
4.5.2 Stress analysis result..................37
CHAPTER 5:..................39
CONCLUSION 39
5.1 Conclusion..................39
5.2 Suggested Future Works 39
REFERENCES 40

List of Figures

Figure 1: A typical LNG Process 1
Figure 2: Major problems in Cryogenic Pipeline 3
Figure 3: ITP LNG PiPiP (Brown, et. al, 2009) 8
Figure 4: Invar sample 11
Figure 5: Different types of bellow 11
Figure 6: Aerogel Insulation (Phalen et.al, 2007) 12
Figure 7: Comparison between test result and FE result (Zheng, et, al. 2012) 15
Figure 8: Research Methodology 18
Figure 9: Project activities 19
Figure 10: Meshing procedure 26
Figure 11: Applied internal pressure load 27
Figure 12: Internal thermal loading 27
Figure 13: External thermal loading 28
Figure 14: Total deformation of SS 304L pipe 31
Figure 15: Stress distribution of SS 304L pipe 31
Figure 16: Temperature distribution of SS 304L pipe 31
Figure 17: Safety factor distribution of SS 304L pipe 32
Figure 18: Total deformation of Kovar pipe 32
Figure 19: Total stress distribution of Kovar pipe 33
Figure 20: Temperature distribution of Kovar pipe 33
Figure 21: Safety factor distribution of Kovar pipe 33
Figure 22: Total deformation of Invar pipe 34
Figure 23: Stress distribution of Invar pipe 34
Figure 24: Temperature distribution of Invar pipe 35
Figure 25: Safety factor distribution of Invar pipe 35
Figure 26: Comparison of ASME standards 36
Figure 27: Test results for three materials 37

List of Tables

Table 1: Pros and cons of carbon steel pipe (Pure Technologist) 4
Table 2: Typical Compositions of pipeline steels (Guo et. al, 2005) 5
Table 3: Percentage effect of strengthening mechanisms (Guo et.al, 2005)........................... 5
Table 4: Nickel base alloy composition.. 6
Table 5: Component of PiPiP (Phalen. A.C, et.al 2007).. 8
Table 6: General Pipeline configuration 9
Table 7: Existing Product type 9
Table 8: Issued and Potential Causes in Pipe-in-Pipe...12
Table 9: Stages of FEM analysis 13
Table 10: Test Methodology conducted by Cox J., et, al. (2003) 15
Table 11: Longitudunal Joint Factor...22
Table 12: List of pipes properties 23
Table 13: Mechanical property of material used 24
Table 14: Wall thickness based on ASME B31.3 30
Table 15: Wall thickness based on ASME B31.4 30
Table 16: Stainless steel 304L result 32
Table 17: Kovar result 34
Table 18: Invar result..35

CHAPTER 1:
INTRODUCTION

1.1 Project Background

In a rapidly growing industry of oil and gas, the need to keep improving on technological advancement is a necessity especially in matters of transporting oil and gas from the well to the processing plant, and from processing plant to the user. There are generally two types of energy pipelines, namely Liquid Petroleum pipelines and Liquid Natural Gas (LNG) pipeline.

Natural gas is a mixture of several hydrocarbon mainly methane (between 70% - 90%). In a gaseous state, LNG takes up about 1/600th the volume of natural gas. The gas is being transported to processing plant for liquefaction process to convert gas into LNG for ease of storage and transport as shown in Fig.1. During treatment process, several processes take place in transforming natural gas into LNG. The natural gas is condensed into a liquid at maximum pressure around 25 kPa and cooling it to -162^{o}C.

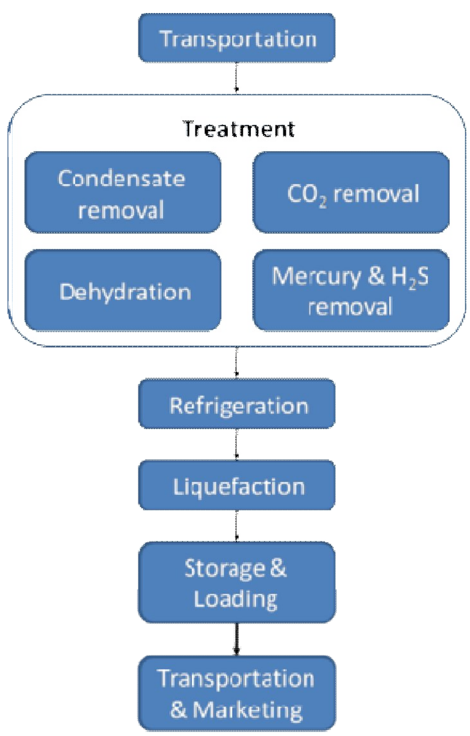


Figure 1: A typical LNG Process

With the increased interests and rapid development in the transportation of LNG, it has come to new revolution on how to transport LNG in an effective way. Traditionally, the system is based on a trestle based civil works in which the pipe are laid on top of it which connect it from a tanker carrying LNG to the onshore facility. This traditional trestle method has several problems to the local authority as it needs to take up land for the construction of the trestle and may be prohibitively costly. Thus an alternative to it is by building a subsea cryogenic pipeline to transport LNG without the need of jetty.

As an alternative to the trestle supporting piping, a subsea pipelines can be installed to transport the LNG from or to an offshore terminal. Also by burying the subsea pipeline, it can help to improve the thermal performance of the pipeline in a hot climate.

Subsea cryogenic pipelines designs to date focus on the use of vacuum systems for insulation and Invar pipe materials to control growth and the differential stress in the pipeline systems (Prescott et.al, 2007). Normal carbon steel pipeline cannot do the job as it need for special flexible and composite pipeline due to the property of LNG which need to be transported under cryogenic temperature of -160^{o}C.

In this research the author is experimenting with a newly developed sandwich cryogenic pipeline which going to be used to operate at platform areas to accommodate with subsea conditions. As this pipeline offer a cheaper alternative solution than the complex trestles system.

1.2 Problem Statement

Subsea cryogenic operating under extreme low temperature can impose several challenges in it. The major challenges for these system include, the managing of pipeline contraction due to the low temperature of the LNG, the thermal efficiency of the insulation system, the reliability of the system, the ease of construction and the ability to monitor, inspect and if necessary, repair in a timely manner. As conceptually shown in Fig. 2.

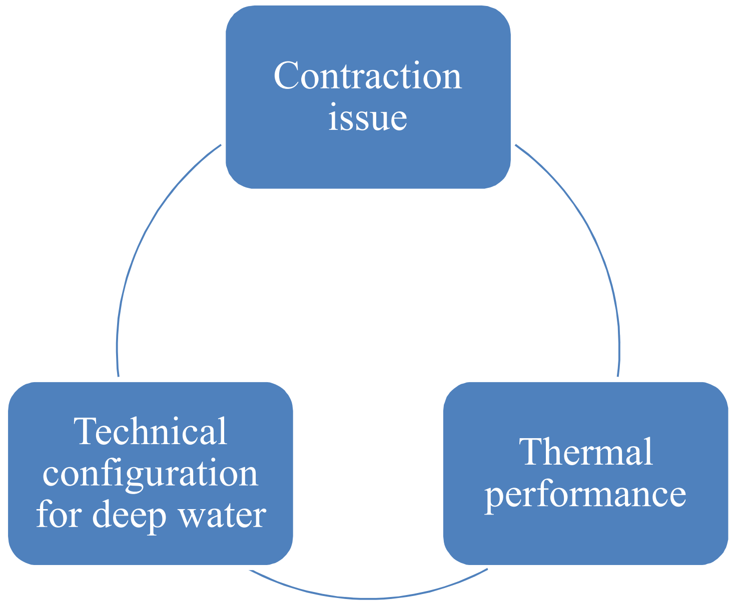


Figure 2: Major problems in Cryogenic Pipeline

1.3 Scope of Study and Objectives

The scope of this research is to carry out stress analysis on a newly developed LNG cryogenic pipeline using finite element modelling (FEM) for three different materials namely stainless steel, 36% nickel (Invar) and 29% nickel (Kovar).. The software that will be used in this research is ANSYS.

Thus, this research is focused on the following objectives:

1. To manually design a pipeline based on the ASME 31.3 Standard.
2. To numerically model stress analysis of the LNG composite cryogenic pipeline.
3. To compare the performance of the LNG cryogenic pipelines of three different materials.

CHAPTER 2:
LITERATURE REVIEW

2.1 Carbon Steel

Carbon steel pipeline is one of the most common types of pipeline being used in industry due to its economical factor and ease of application.

The main benefit of the steel pipe is on its strength. These pipes do not crack under most impacts and can operate under very high pressure. Some of the advantages and disadvantages of carbon steel pipe are tabulated below.

Table 1: Pros and cons of carbon steel pipe (Pure Technologist)

Advantages	Disadvantages
High tensile strength	Prone to external corrosion
High compressive strength	Electrolysis prone
Range of corrosion protection system	Jointing requires skilled welders
Wide range of diameters and wall thickness	Internal/external corrosion protection system add to price
Welded joints give continuity	Coatings and lining can get damaged during installation by third parties

2.1.1 Basic Carbon Steel Design

Carbon steel pipeline is a material which the constituent of metal is combination of carbon in the range of 0.12 – 2.0% with other metals such as Manganese, Silicone and Aluminium. If the material consists of more than 2% carbon it is termed as “cast iron”. Carbon steel pipeline is being used widely due to its economic reasons and usually being used for production and transmission of oil and gas, and also for water injection systems. Table 2.2 shows some combination of carbon steel pipeline used in the industry.

Table 2: Typical Compositions of pipeline steels (Guo et. al, 2005)

Pipeline Grade/Wall		Maximum Composition										
		C	Mn	Si	Ni	Cu	V $x10^2$	Nb $x10^2$	Ti $x10^2$	B $x10^3$	P $x10^2$	S $x10^3$
Examples of Actual Pipeline Steel												
X65	16	0.02	1.59	0.14				4	1.7	1	1.8	3
X65	25	0.03	1.61	0.16	0.17			5	1.6	1	1.6	3
X65	25	0.06	1.35		0.25	0.33	7	4	1.8		2.5	5
X70	20	0.03	1.91	0.14				5		1	1.8	3
X70	20	0.08	1.6			0.04		7				

2.1.2 Material Properties

The material used in pipeline is important as it determine on the strength of the pipeline itself. According to Palmer and King (2008), pipeline steel must have strength while retaining ductility, fracture toughness, and weldability. The author further explain that the balances of these properties are required depending on the intended use and purpose of the pipeline itself.

There are some ways steel strength can be increased by using one or a combination of the following mechanisms:

- Solid solution strengthening
- Grain refining
- Precipitation strengthening
- Transformation strengthening
- Dislocation strengthening

Table 3 shows the typical percentage effects of the strengthening processes for pipeline strengthening.

Table 3: Percentage effect of strengthening mechanisms (Guo et.al, 2005)

Strengthening option	Mechanism	% Effect on Strength
Base line strength		18
Addition of silicon and nitrogen	Solid Solution	8
Addition of manganese	Solid Solution	12
Ferrite grain size	Grain refining	45
Micro-alloying	Precipitation	17

2.1.3 Pipe Fabrication

In the oil and gas industry, the pipeline is made by one of four fabrication methods.

Seamless method has no longitudinal weld seam. In other word it can be consider as one solid piece of steel. A *billet* is cut from slab and heated and formed by rollers to produce a length of pipe. The general type of piercing mill is The Mannesmann mill.

Electrical resistance welded (ERW) pipe is formed from coiled plate of steel flattened and pass through a sequence of rolls to form the pipe and ready for welding of the longitudinal seam. The longitudinal seam weld is made by ERW.

Submerged Arc Welded (SAW) or sometimes called U-O-E pipe is formed from individual plate of steel by forming a plate into a U, then into a tube (O).

Spiral Weld is manufactured exactly like SAW but in this process only the weld seam takes on a spiral appearance due to the way the skelp is rolled.

2.2 Low Expansion Nickel Alloy

Operating under cryogenic temperature need a specialize material that have very low expansion rate when exposed under cryogenic condition. Nickel alloy is known to be a solid strengthener, a mild hardenability agent as a means for promoting high toughness especially at low temperature.

In this research, a 29% Nickel is chosen to be the proposed material to be used for the sandwich cryogenic pipeline. 29% Nickel alloy also known as Kovar and Alloy K is an iron-nickel-cobalt alloy designed for precise and uniform thermal expansion characteristics. Adding nickel to iron alloy can produce a reduced coefficient of thermal expansion. Table 4 below shows the composition of various nickel alloy material.

Table 4: Nickel base alloy composition

Alloy	Ni %	Fe %	Others
Stainless Steel	8-10	-	Chromium 17%-19%
29% Nickel alloy	29.0	53.0	Cobalt 17%
36% Nickel alloy	36.0	64.0	-

2.3 Pipe-In-Pipe-In-Pipe (PiPiP) Pipeline

Design of subsea LNG pipeline have a lot of challenges such as low operating temperature (-160^{o}C) and this has caused for the pipe to have multiple pipe walls, and differential expansion material as well insulation types. Some of the design considerations of LNG loading/offloading pipelines present several design challenges:

- Low temperature (-160^{o}C)
- Relatively long distance
- High thermal performance requirements
- Low risk tolerance
- Expensive

2.3.1 Pipe-in-Pipe-in-Pipe (PiPiP) Design Concept

The general idea of this pipe is to have the main pipe to be covered by two layers of outer pipe. The main characteristic of the design based on ITP (2007) are:

- Triple-walled with sacrificial outer pipe.
- Inner pipe material, 36% Nickel-Iron (Invar).
- High performance Izoflex, microporous insulation
- Intermediate and outer pipes both designed for collapse

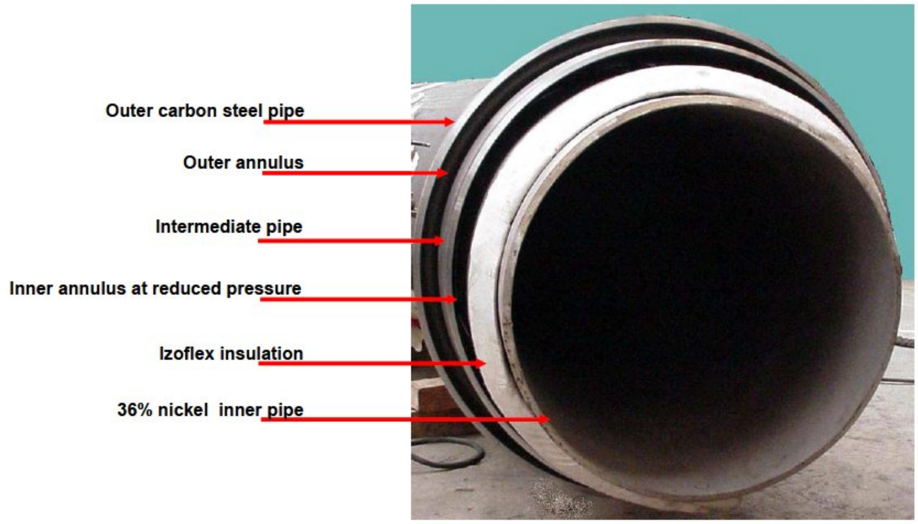


Figure 3: ITP LNG PiPiP (Brown, et. al, 2009)

The details of each component in a PiPiP are explained based on the material and function of each material on Table 4 below.

Table 5: Component of PiPiP (Phalen. A.C, et.al 2007)

Component	Material	Function
Inner pipe	36% Nickel-Iron (Invar)	• Invar allow the pipe to be less in expansion and contraction due to very low temperature of LNG
Intermediate and Outer pipe	Carbon Steel	• Designed for collapse in the maximum water depth. • Provide protection from external damage.
Inner annulus	Partial Vaccum	• Izoflex insulation, for thermal performance • Act as a very sensitive leak detection system.
Outer annulus	Filled with dry Nitrogen	• For leak detection system

2.3.2 Pipeline Configuration

Many types of subsea pipeline configurations are now being tested for use in offshore applications. There are several differences between available subsea cryogenic pipeline systems on the basis of cost and thermal performance based. Eight configurations have been compared as tabulated on Table 6 below.

Table 6: General Pipeline configuration

Insulation Type	Materials for contraction	Casing
Vacuum Insulated	9% Ni product pipe	9% Ni
Vacuum Insulated	Bellow Stainless steel	Steel
Aerogel filled annular space	9% Ni	Steel
Aerogel blanket	9% Ni	Steel
Fumed Silica with vacuum	Invar	Steel
Aerogel blanket	Invar	Steel
Polyurethane	Invar	HDPE
Polyurethane	9% Ni	Steel

2.3.3 Existing Cryogenic Pipeline

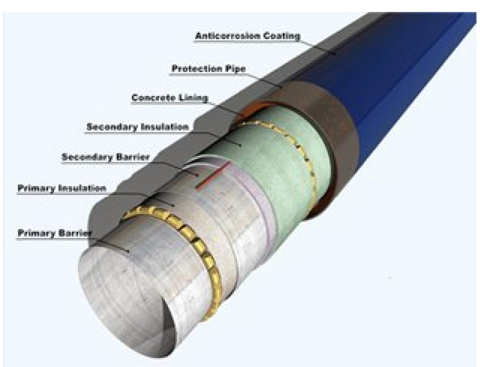
At present, only few existing cryogenic pipeline in LNG industry. Among the players that involve in the development of subsea cryogenic pipeline are Fluor, GTT (Pluto II), and Total. Table 7 shows the current existing subsea cryogenic pipeline done by few industries.

Table 7: Existing Product type

<table>
<tr><th>Product</th><th>Product Information</th><th>Pipe Structure</th></tr>
<tr><td>

Pluto II

by Gaztransport & Technigaz (GTT)



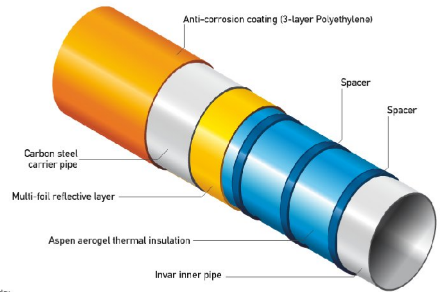
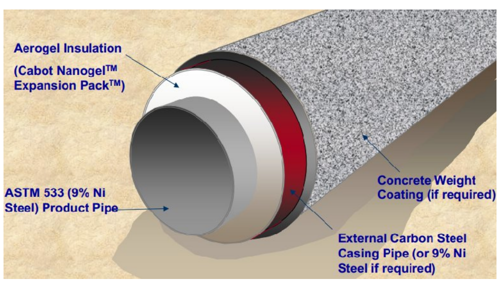
</td><td>

- Double containment pipe
- Double barrier principle
- Fully redundant containment
- Fully redundant monitoring system

</td><td>

- Product line made of 36% nickel alloy
- Primary insulation layer
- Secondary insulation layer
- HD Concrete weight lining

</td></tr>
</table>

<table>
<tr><td></td><td>Tested in cryogenic environment</td><td>Carbon steel carrier pipe
Foam spacer</td></tr>
<tr><td>ITP InTerPipe
by TOTAL

</td><td>Triple- wall (PiPiP)
Protection against external damage
Acceptable level reduction for water ingress or failure of external pipe
Tested in cryogenic environment</td><td>36% Ni alloy
Intermediate and outer pipes
Izoflex™ insulation material</td></tr>
<tr><td>ITP InTerPipe
by Fluor

</td><td>Highly efficient insulation in an ambient environment
Eliminates the need for expensive alloys and the vacuum pipe-in-pipe system</td><td>9% Ni steel
Ambient pressure in annular space
Aerogel insulation</td></tr>
</table>

2.4 Problems of Cryogenic Pipeline

2.4.1 Contraction Problem

Operating in cryogenic environment possess several challenges for the pipeline itself. Among the challenges is the contraction problem. A contraction will cause loss in strength in pipe and changes in diameter which will affect the flow assurance of the

LNG itself. According to Phalen and Prescott (2007), at present, there are mainly two methods to overcome this contraction:

- The use of Invar or other alloy with ultra-low thermal expansion coefficient.
- Use of bellows, one in each segment (about 15 m long) of the pipeline, which is a self-contained pipe-in-pipe segment vacuum insulation, and one larger bellows on the external casing pipe larger intervals (about 150 m long).

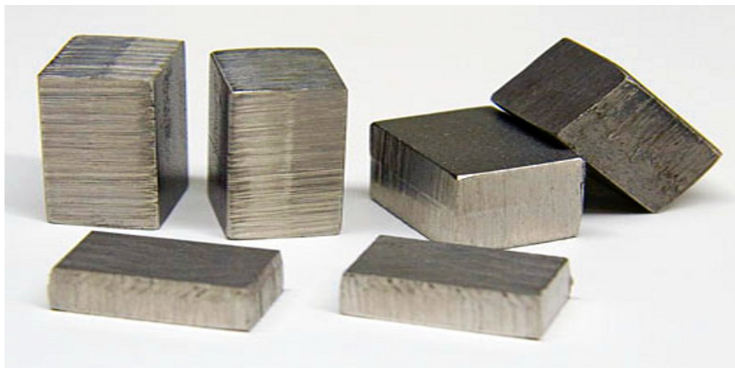


Figure 4: Invar sample

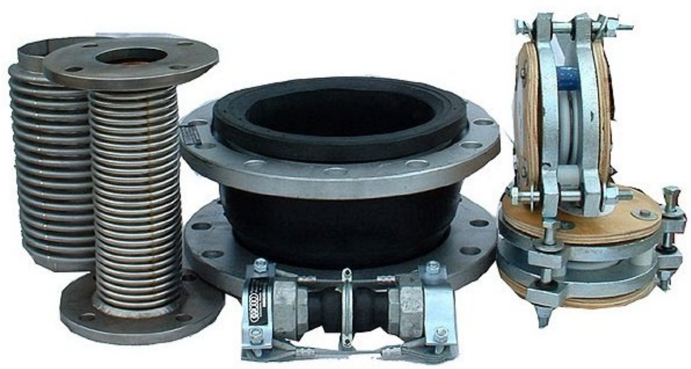


Figure 5: Different types of bellow

In matter of technical, both methods are feasible but also suffer major disadvantages in cost, reliability, durability, or maintenance requirement. As Nickel prices tripling over last few years, it has caused the cost of Invar to be drastically expensive to order and produce.

While bellows are knows to also have a high cost and there has been a continuous question on the reliability and maintenance of large diameter thin walled bellows if used in a subsea application where installation stresses might damage the units.

2.4.2 Thermal Performance

According to Phalen and Prescott (2007), currently there are several methods for addressing thermal performance for a cryogenic pipeline:

- Use of conventional polyurethane or similar insulation systems such as fumed silica
- Use of high efficiency Aerogel insulation systems
- Use of vacuum insulated pipe-in-pipe

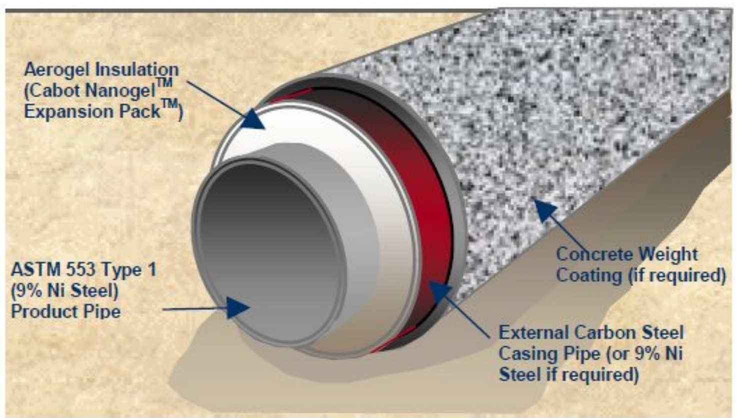


Figure 6: Aerogel Insulation (Phalen et.al, 2007)

The vacuum has a higher thermal performance compared to the conventional insulation system but it will cause a higher maintenance costs and reliability.

Both systems to handle contraction and thermal performance have their own problem for different types of material used. The summary of all issues for each component are summarize in Table 8.

Table 8: Issued and Potential Causes in Pipe-in-Pipe

Pipe Component	Issues	Potential Causes
Inner Pipe	The LNG will be leak out into the annular region, and contact with the outer pipe will cause: - Loss of insulation of property - Increase internal pressure due to vaporized LNG	- Peak pressure during transient conditions (water hammer) - Thermal cycling of pipeline - Cavitation at bulkhead - Material transition failure - Thermal transient during

		startup - Weld failure - Hydrotest of pipeline with water may leave water behind (pipe corrosion, ice formation)
Insulation	Loss of insulation will cause: - Freezing in pipeline - An increase of boil off rate - Potential of brittle failure of outer pipe if made of carbon steel	- Contamination of insulation - Improper installation - Insulation damage due to welding work - Damage during pipeline installation - Aging of insulation
Outer Pipe	Water ingression will cause: - Losing all insulation capability and freezing of pipe - LNG evaporation - Pressure build up - Inner pipe may collapse due to high external pressure from sea water.	- Mechanical damage during installation - Corrosion - Buckling due to improper support for pipeline span - Weld defects - Impact from external sources - Overstressed due to natural events

2.5 Finite Element Modelling

The finite element method (FEM) has been used widely in many areas of engineering problem for its numerical solution. With the advancement of CAD system, several alternative configurations of an engineering design can be analyse before a prototype is built.

Based on Table 9, a complete finite element analysis is a logical interaction of the three stages:

Table 9: Stages of FEM analysis

Pre-Processing	Preparation of data:

	- Nodal Coordinate - Connectivity - Boundary conditions - Loading - Material information
Processing	Stiffness generation Stiffness modification Solution of equations Evaluation of nodal variables
Post Processing	Presentation of results: - Deformed configuration - Mode shapes - Temperatures - Stress distribution

Several test on cryogenic pipeline has been conducted previously, among those test is the impact damage on Pipe-in-Pipe systems using FEM done by Zheng, et, al. (2012). The purpose of the test was to understand the performance of Pipe-In-Pipe system under external force due to accident by falling anchor in high fishing area. The research conducted both experimental and numerical FEM test testing on two models; single pipe and Pipe-In-pipe model.

The result of the research is plotted as Fig. 7 below:

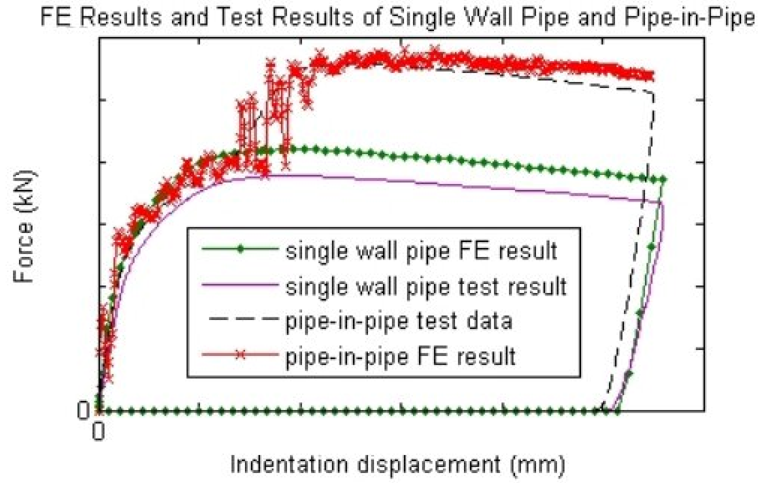


Figure 7: Comparison between test result and FE result (Zheng, et, al. 2012)

The Pipe-in-Pipe results show higher resistance to damage impact compare to the single wall pipe as the Pipe-in-Pipe system has different mechanical behaviour.

2.6 Experimental Test on Pipe-in-Pipe System

Another research has been conducted by Cox, et, al. (2003) on flexible cryogenic pipeline. The research conducted several experimental tests on a flexible cryogenic pipe.

The paper addresses the testing of a cryogenic flexible, and its integration and qualification as part of an overall offshore system. The prototype used 16” ID up to 24” ID with minimum service life of 5 years with safety factor of 10 relative to fatigue life. Table 5 shows the methodology conducted by the researcher.

Table 10: Test Methodology conducted by Cox J., et, al. (2003)

Test	Description	Result
Bellow Testing	Focus on the inner layer made of corrugated bellows.	- The girth weld did not leak - Leaks through fatigue induced cracks always occurred on the longitudinal

		welds. - Stress related axial fatigue results meet the required standard by Expansion Joint Manufacturers Association (EMJA). - Bending related fatigue results did not reach EMJA.
Thermal Calculation	To get a positive temperature on the exterior layer all times. This was verified using the THERM computer analysis program.	
Testing of the flexible layers function	To test the effect of pressure and tension on the armour wires, stiffness calculations (axial, bending and torsion, thermal contraction, stress induced fatigue due to internal pressure and damaging pull.	
Small scale test	To determine the actual fatigue characteristics compared to theoretical calculations.	No mechanical damage to the flexible structure or the end fitting
Full scale dynamic tests	To confirm: - The integrity of the pipe in normal condition. - To provoke a fatigue related leak according to the small scale tests	The overall components were proven to be satisfactory in fatigue mode.
Burst test	To test for destructive burst	- No leaks in the girth weld areas and the burst occurred towards the centre of sample. - The double cross wound armour layers performed their function as required.

CHAPTER 3:
METHODOLOGY

3.1 Research Methodology

This research will be conducted based on the following activities towards the completion of Final Year Project (FYP) as shown in Fig. 8:

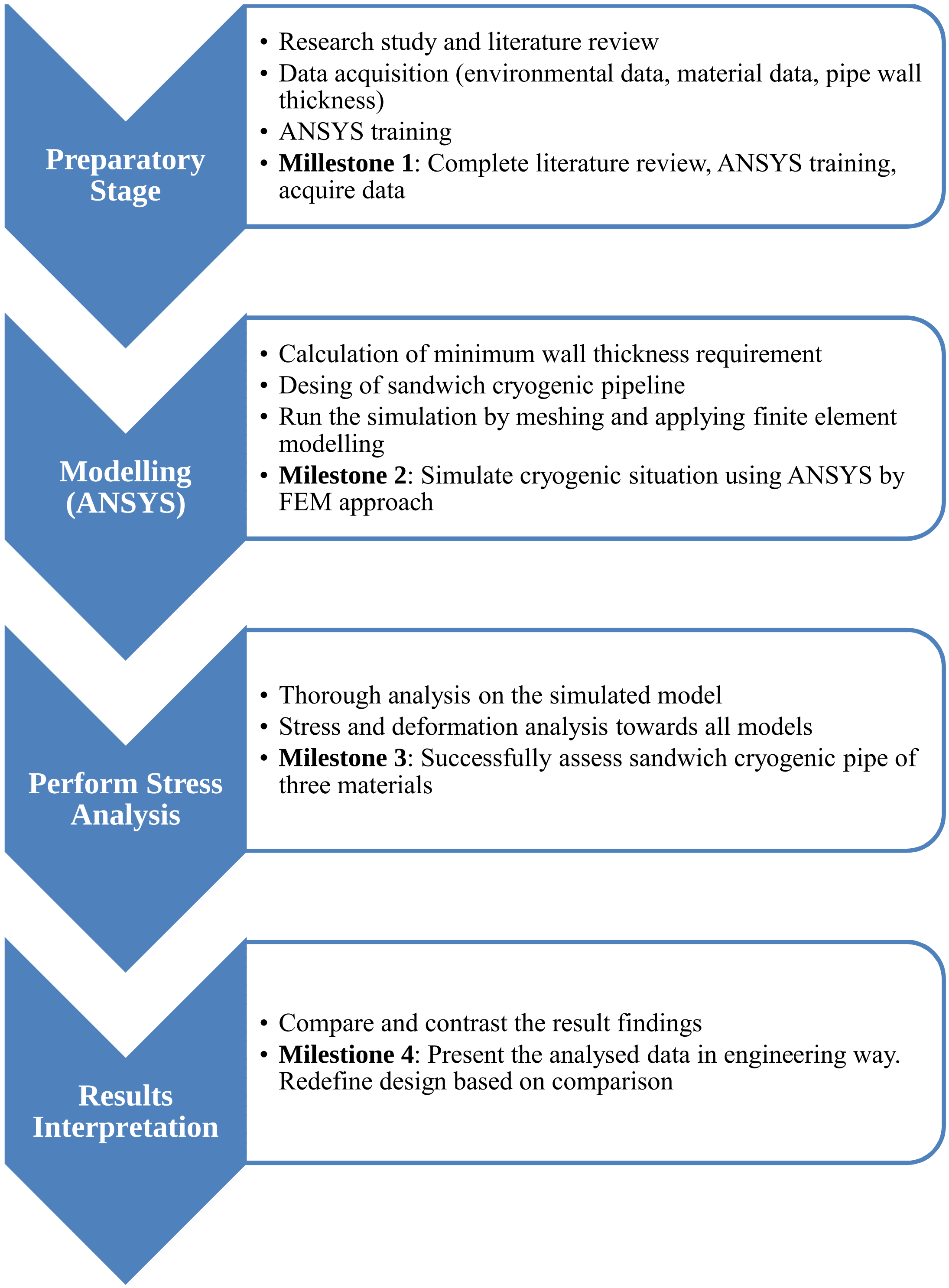
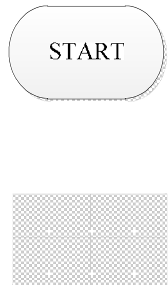


Figure 8: Research Methodology

Fig. 9 below shows the project activities for this research



3.2 Pipeline Design

Marine pipeline design is usually carried out in three stages:

- Conceptual engineering
- Preliminary engineering
- Detail engineering

According to Guo (2005), during conceptual engineering, issues of technical feasibility are revealed and non-viable options are eliminated and the outcome of this stage allows for scheduling of development and rough estimate of cost. The preliminary engineering identify system concept such as pipeline size and grade, prepare authority applications, and provides design details to order pipeline. In the detail engineering phase, final detail is completed to define the technical input for all procurement and construction tendering.

3.3 Design Data

There are many parameters that can affect the pipeline design and operations. Below are the lists of data that will affect the pipeline design:

- Reservoir performance
- Fluid and water compositions
- Fluid PVT properties
- Sand concentration
- Sand particle distribution
- Geotechnical survey data
- Meteorological and oceanography data

In this thesis, the author will focus on the reservoir performance specifically on the production profiles.

3.3.1 Production Profiles

One of the most important data for pipeline sizing is production profile. It gives information on how the oil, water, and gas flow rates will change with time for the whole field life. Reservoir engineer performed reservoir simulations to generate production profile.

3.4 Diameter and Wall Thickness

In designing pipeline, it consists of selection of pipeline diameter, thickness, and material to be used. Pipeline diameter is selected on the basis of flow capacity required to transport production fluids at an expected rate provided by the oil or gas well.

3.4.1 Piping Codes

Based on American National Standard Institute (ANSI) and the American Society of Mechanical Engineers (ASME) specify wall thickness requirements as follows:

- ANSI/ASME Standard B31.1 (Power Piping)
- ANSI/ASME Standard B31.3 (Chemical Plant and Petroleum Refinery Piping)
- ANSI/ASME Standard B31.4 (Liquid Transportation Systems for Hydrocarbons, Liquid Petroleum Gas, Anhydrous Ammonia, and Alcohols)
- ANSI/ASME Standard B31.8 (Gas Transmission and Distribution Piping System)

For offshore LNG Pipeline consideration, it is better to use the ANSI/ASME Standard B31.3. This standard focus more on offshore piping facilities and it is more stringent compare to ANSI/ASME B31.4 and B31.8

3.4.2 Design Procedure

Pipeline wall thickness is determined based on the design internal pressure or the external hydrostatic pressure. In this paper, the author recommends the following procedure for designing pipeline wall thickness:

i. Calculate for the wall thickness both Zone 1 and Zone 2 due to internal pressure *(Pressure containment calculation)*

<u>Pressure Containment Calculations *(based on ANSI/ASME Standard B31.4 or PTS)*</u>

In pipeline engineering, the area of pipeline being laid out is divided into two zones which have their own design factor.

Zone 1 : area free from disturbance. (Design factor = 0.72)

Zone 2 : within 500 m radius from platform. (Design factor = 0.5)

Pressure Containment Equation:

$$t_z = \frac{P_i D}{2FES_y} + C \tag{3.1}$$

Pi	=	inlet Pressure (MPa)
D	=	diameter (mm)
F	=	design Factor
E	=	longitudinal Joint Factor
S_y	=	minimum Yield Strength
C	=	corrosion allowance

Table 11: Longitudunal Joint Factor

TYPE	FACTOR
Seamless Double submerged arc weld Flash weld	1.0
Electric fusion (arc)	0.80
Furnace butt weld	0.60

<u>Pressure Containment Calculations *(based on ANSI/ASME Standard B31.3)*</u>

Pressure Containment Equation:

$$t = C + t_{th}\left[\frac{P_i D}{2(SE + PY)}\right]\left[\frac{100}{100 - T_{ol}}\right] \tag{3.2}$$

t	=	minimum wall thickness design.
C	=	corrosion allowance
t_{th}	=	thread or groove depth
P_i	=	allowable internal pressure in pipe
D	=	outside diameter of pipe
S	=	allowable stress for pipe

E	=	longitudinal weld-joint factor
Y	=	derating factor
T_{ol}	=	manufacturer allowable tolerance

3.5 Pipeline Stresses and Load Identification

At the initiation stage, two factors that affecting the performance of an LNG pipeline need to be identified which are stresses and loads. Internal pressure, external pressure, axial, and thermal effect need to be taken into consideration on this research as the classification of the pressure loading are important.

3.6 Cryogenic Pipeline Modelling using Finite Element Modelling (FEM)

An accurate analysis of cryogenic pipeline is required and it will inevitably need the use of computer software. With the help of finite element modelling (FEM) software, it allows a wide range of analysis for the cryogenic pipeline research. Various shapes of model and materials can be involved using FEM. The ANSYS® Workbench™ version 15.0 allows the user to simulate the critical area (the area where it expected to fail) and to simulate the deforming surfaces. The multiphysic capabilities of ANSYS enable the user to improve user product development processes, reduce analysis time, and improve product innovations and performances.

Modelling of cryogenic pipeline involves few stages before the analysis can be done. The stage consists of assigning pipe model properties, analysis system, modelling, meshing, defining loads and analysing results from solution.

3.6.1. Pipe Model Properties

For the purpose of this research, four type of pipe was modelled based on several different parameters of outside diameter and pipe schedule. Table 12 shows the list of pipe diameter being used in this research.

Table 12: List of pipes properties

Material	Outside	Schedule	Wall thickness	Inner Diameter

	Diameter		(mm)	(mm)
Inner Pipe				
Stainless Steel	6" (168.3 mm)	STD	7.1	154.1
9% Nickel (Kovar)	6" (273.0 mm)	STD	7.1	154.1
36% Nickel (Invar)	6" (168.3 mm)	STD	7.1	154.1
Outer Pipe				
Stainless Steel	8" (219.1 mm)	Sch. 40	8.2	202.7
9% Nickel (Kovar)	8" (219.1 mm)	Sch. 40	8.2	202.7
36% Nickel (Invar)	8" (219.1 mm)	Sch. 40	8.2	202.7

3.6.2 Mechanical Property of Pipe Material

Table 13 below shows the mechanical property of three materials that is being used in this research.

Table 13: Mechanical property of material used

Property	Stainless Steel	29% Nickel	36% Nickel
Density (kg/m^3)	7750	8000	8055
Thermal expansion (C^{-1})	1.7E-05	5.5E-06	1.2E-05
Young Modulus (Pa)	1.93E+11	1.38E+11	1.41E+11
Poisson Ratio	0.31	0.29	0.29
Bulk Modulus (Pa)	1.69E+11	1.09E+11	1.12E+11
Shear Modulus (Pa)	7.37E+10	5.35E+10	5.47E+10
Yield strength (Pa)	2.07E+08	2.70E+08	5.85E+08
Tensile strength (Pa)	5.86E+08	5.18E+08	6.9E+08
Thermal Conductivity (W/mC)	15.1	17	10

3.6.3 Analysis System

STATIC STRUCTURAL – A linear static structural analysis is performed to get the response of the pipe structure under applied static loads. This analysis is used to determine the displacements, reaction forces, stresses, and strains.

For a linear static structural analysis, the displacement {x} are solved for in the matric equation below:

$$[K]\{x\} = \{F\} \tag{3.3}$$

This result in certain assumptions related to the analysis:

- [K] is essentially constant
  - Linear elastic material behaviour is assumed
  - Small deflection theory is used
  - Some nonlinear boundary conditions may be included

- {F} is statically applied
  - No time-varying forces are considered
  - No inertial effects are included

STEADY STATE THERMAL ANALYSIS – A steady state thermal analysis calculated the effect of steady thermal loads on system or component. It is being used to determine temperatures, thermal gradients, heat flow rates, and heat fluxes in the pipe that are caused by thermal load that do not vary over time.

3.6.4 Modelling

All 3D models of the pipe were generated by using ANSYS Workbench. The required structural material properties are determined here which are Young's Modulus and Poisson's Ratio for linear static structural analyses. In which for this research, Stainless Steel were to be used as the similar replacement for low Invar (9% Ni) material.

3.6.5 Meshing

GENERAL MESHING – To run an analysis it is required for the model to be mesh first. A displacement field compatible with applied boundary condition is produced from displacement polynomial which represented by meshing field variable. For this research, element size sets to default setting so it will automatically generated.

General Meshing procedure:

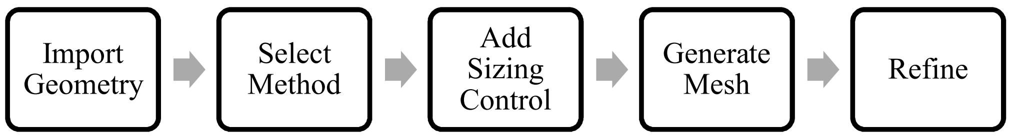


Figure 10: Meshing procedure

3.6.6 Defining Loads

PRESSURE – One loads are applied on the inner pipe surface. The load was applied on the internal surface of the pipeline to represent the internal pressure subjected by the LNG pressure which is 1.0 MPa (10 atm).

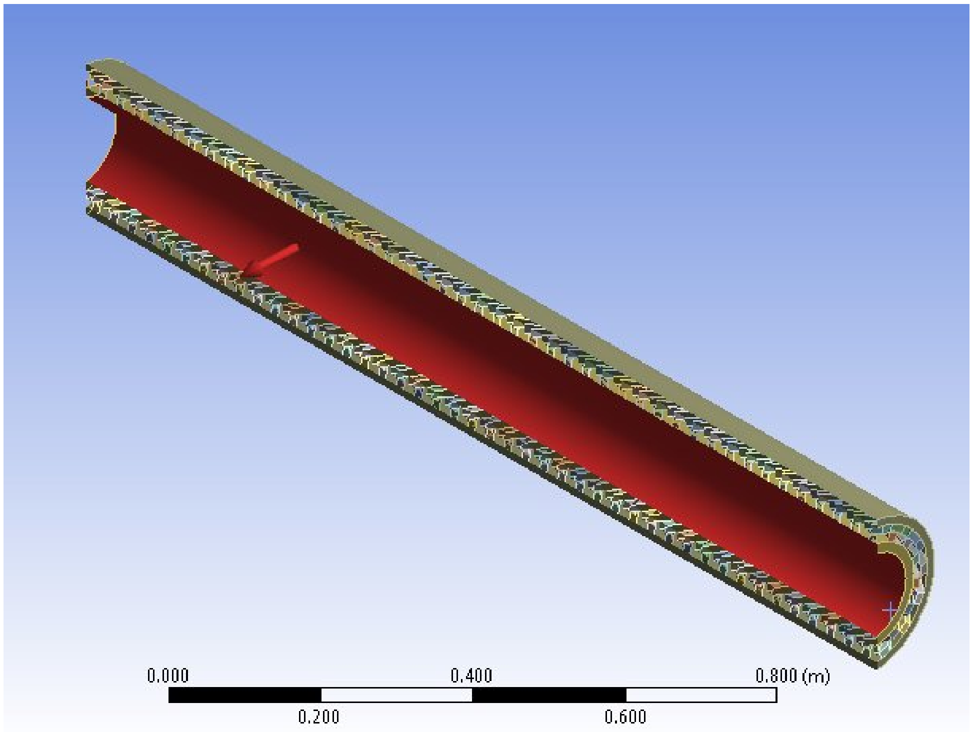


Figure 11: Applied internal pressure load

THERMAL LOADING – The pipe temperature is in cryogenic mode which the internal temperature is set to be -163^{o}C and outside temperature to be 30^{o}C.

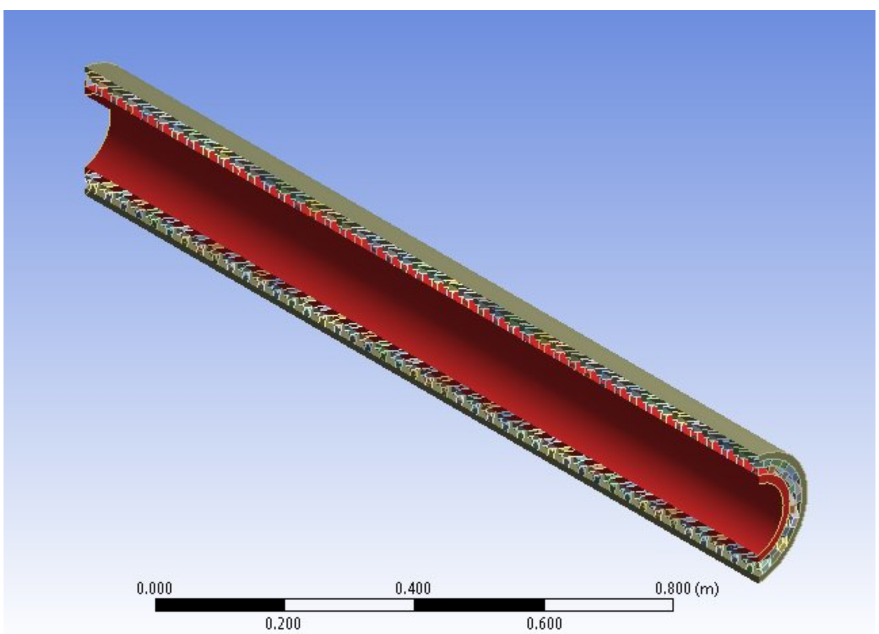


Figure 12: Internal thermal loading

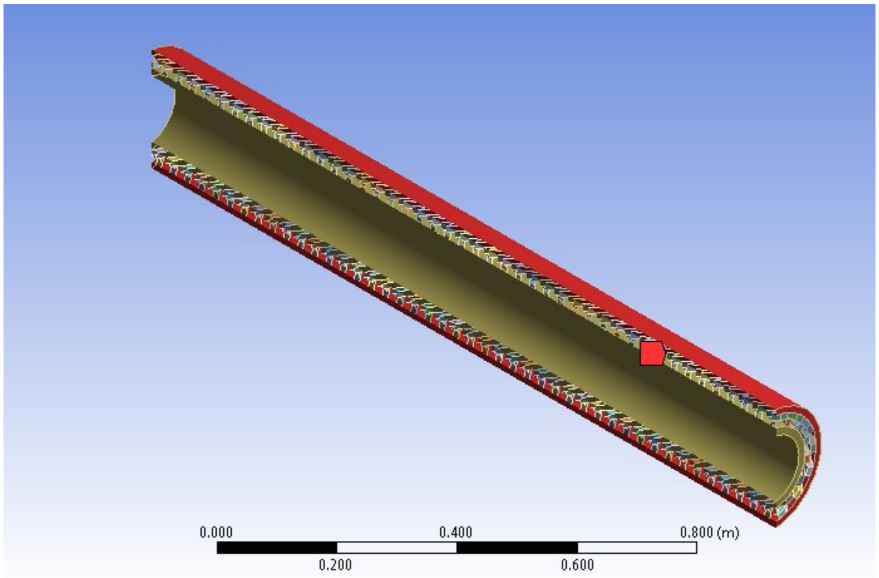


Figure 13: External thermal loading

3.6.7 Solution

TOTAL DEFROMATION – In this research, the target of this result is to find out which material is having the less deformation occurring under operating pressure. The lower the deformation value, the better the performance.

EQUIVALENT VON-MISES ELASTIC STRESS/STRAIN – In this case, the definition of maximum stress is the amount of stress the material is experiencing under the same operating condition. The von Mises or Equivalent stress, σ_e is related to principle stress by the equation:

$$\sigma_e = \left(\frac{1}{2}[(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2]\right)^{\frac{1}{2}} \quad (3.4)$$

Equivalent (von misses) strain, ε_e is computed as:

$$\varepsilon_e = \frac{1}{1 + \upsilon'}\left(\frac{1}{2}[(\varepsilon_1 - \varepsilon_2)^2 + (\varepsilon_2 - \varepsilon_3)^2 + (\varepsilon_3 - \varepsilon_1)^2]\right)^{\frac{1}{2}} \quad (3.5)$$

Where:

υ' = effective Poisson' ratio

Von mises stress was used in this research because it allows any arbiter three-dimensional stress state to be represented as a single positive stress value.

TOTAL HEAT FLUX – Total heat flux is a vector quantity which is to determine the transfer of heat energy through a given surface per unit surface. Heat flux is the amount of heat energy absorbed by the material to make itself contract.

TEMPERATURE – Temperature is a scalar quantity and has no direction associated with it. It is used to know the temperature distribution along the component.

MAXIMUM FRICTIONAL STRESS - This research is done on a pipe-in-pipe configuration. A slight contraction on each pipe will occur when exposed under cryogenic condition.

MINIMUM SAFETY FACTOR - It is the ratio of the maximum stress the material withstand to the maximum stress it is experiencing.

MAXIMUM STRESS RATIO – The ratio between longitudinal stress and hoop stress in the pipeline. The value should be approaching near 1.0 for better performance as it means both stress are synchronize and it will simulate the sandwich configuration as one body.

CHAPTER 4:
RESULT AND ANALYSIS

The results in this research that is included in this section gives high emphasis on the interpretation and discussion of the effect of different material properties toward the internal pressure and temperature applied on it. Note that all simulations pictures may look similar, but each of it is off different values.

4.1 Calculated Wall Thickness

Calculation of wall thickness based on two standards; ASME 31.3 and ASME 31.4

4.1.1 ANSI/ASME B31.3 Standard

Table 14 shows the calculation result for B31.3 Standard.

Table 14: Wall thickness based on ASME B31.3

Material	Wall Thickness (mm)
Stainless Steel 304L	5.710
29% Nickel (Kovar)	5.011
36% Nickel (Invar)	3.819

4.1.2 ANSI/ASME B31.4 Standard

Table 15 shows the calculation result for B31.3 Standard.

Table 15: Wall thickness based on ASME B31.4

Material	Wall Thickness (mm)
Stainless Steel 304L	2.941
29% Nickel (Kovar)	2.233
36% Nickel (Invar)	1.031

4.2 Simulated Stainless Steel 304L Pipeline.

The pictures below are the simulated stress analysis for stainless steel 304L pipe. This type of material is commonly used in normal trestle LNG transfer from shore plant to vessel.

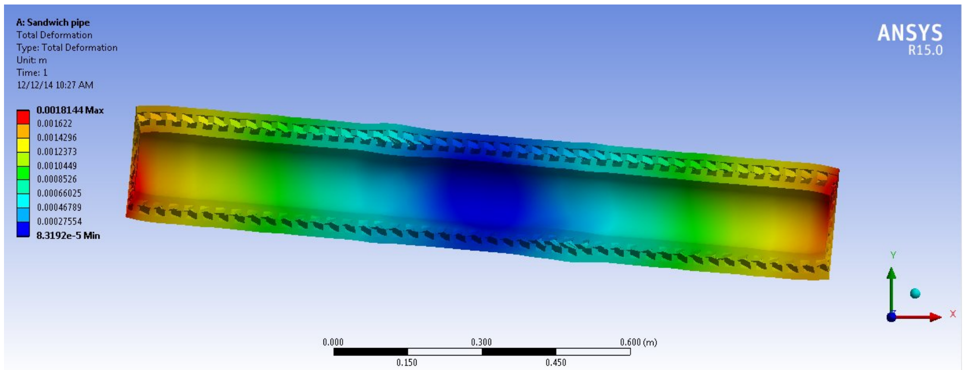


Figure 14: Total deformation of SS 304L pipe

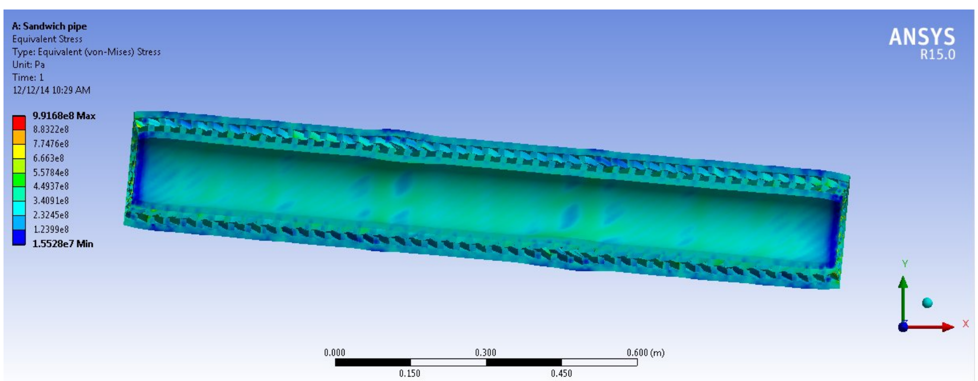


Figure 15: Stress distribution of SS 304L pipe

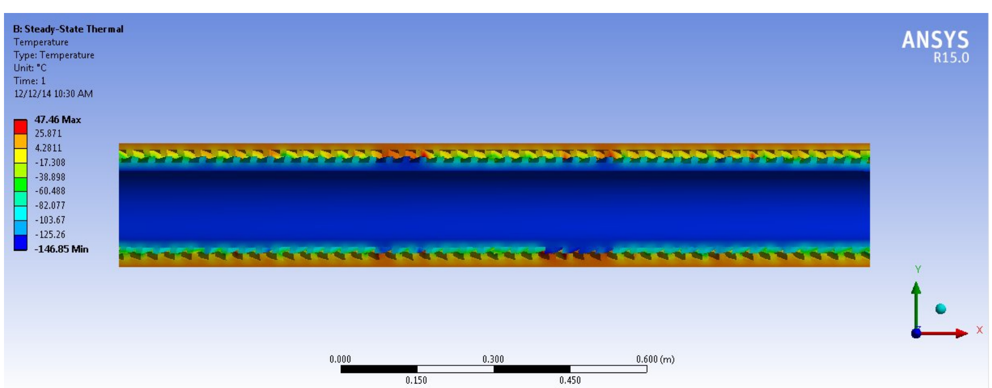


Figure 16: Temperature distribution of SS 304L pipe

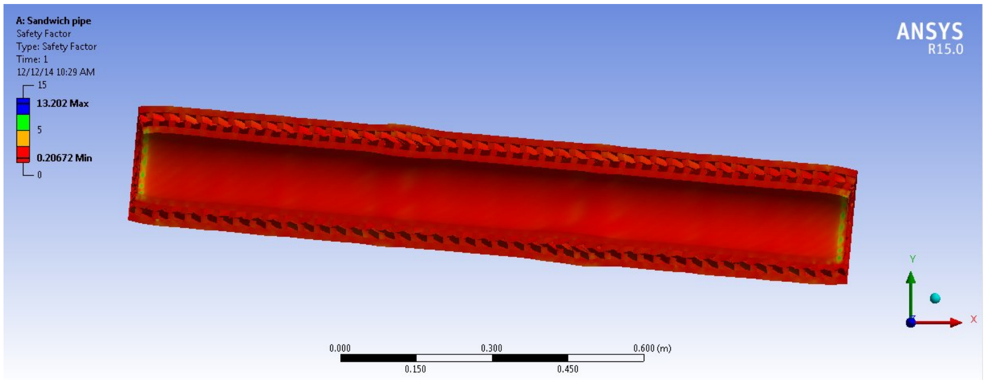


Figure 17: Safety factor distribution of SS 304L pipe

Table 16 below shows the overall result of stainless steel 304L pipeline configuration.

Table 16: Stainless steel 304L result

Total deformation	1.8144E-003	m
Max. strain	5.335E-003	m/m
Max. stress	9.9168E+008	Pa
Minimum safety factor	0.20672	Pa
Maximum stress ratio	4.6375	
Maximum frictional stress	1.669E+008	
Total heat flux	1.4789E+005	W/m^3

4.3 Simulated 29% Nickel (Kovar) Pipeline.

The pictures below are the simulated stress analysis for the proposed 29% Nickel Pipeline.

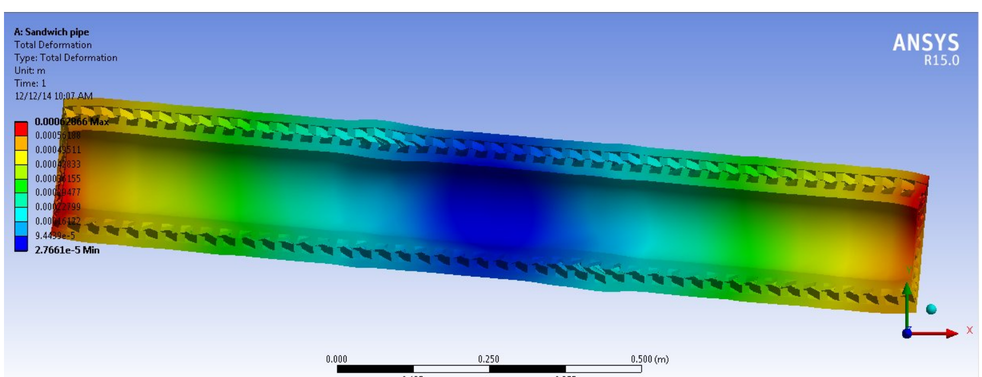


Figure 18: Total deformation of Kovar pipe

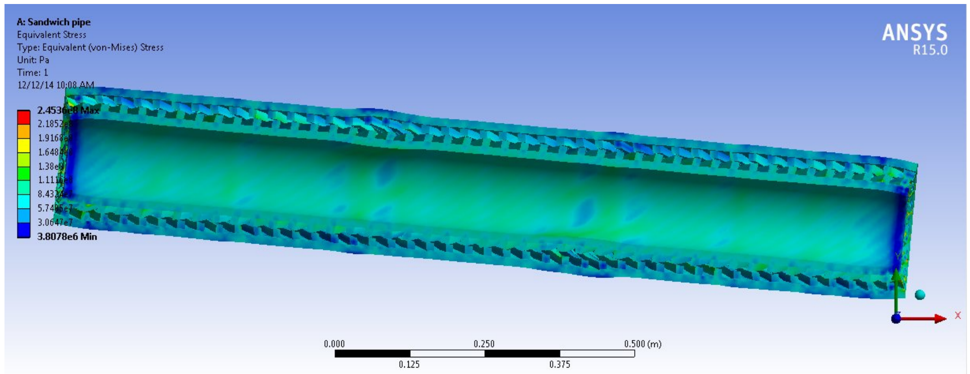


Figure 19: Total stress distribution of Kovar pipe

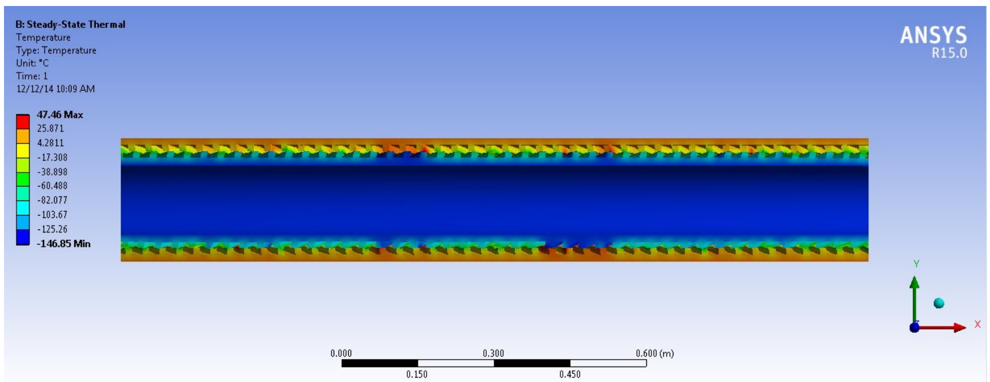


Figure 20: Temperature distribution of Kovar pipe

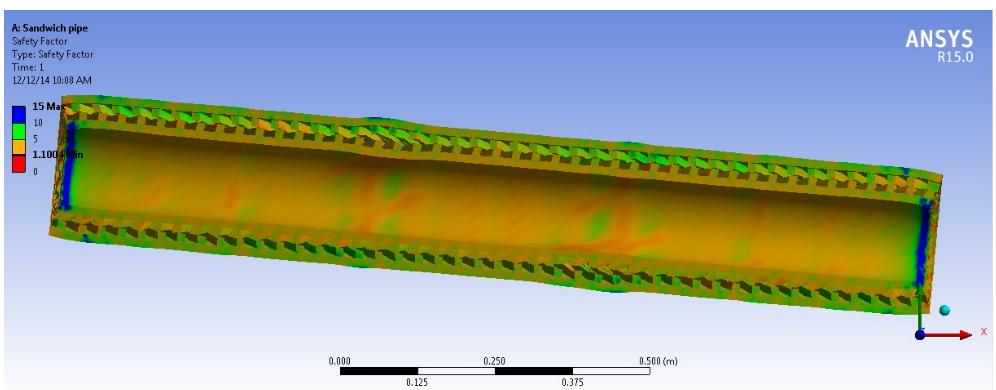


Figure 21: Safety factor distribution of Kovar pipe

Table 17 below shows the overall result of Kovar pipe configuration.

Table 17: Kovar result

Total deformation	6.2866E-004	m
Max. strain	1.8173E-003	m/m
Max. stress	2.4536E+008	Pa
Minimum safety factor	1.1004	Pa
Maximum stress ratio	0.90873	
Maximum frictional stress	4.2084E+007	
Total heat flux	1.7958E+005	W/m^3

4.4 Simulated 36% Nickel (Invar) Pipeline.

The pictures below are the simulated stress analysis for the 36% Nickel Pipeline.

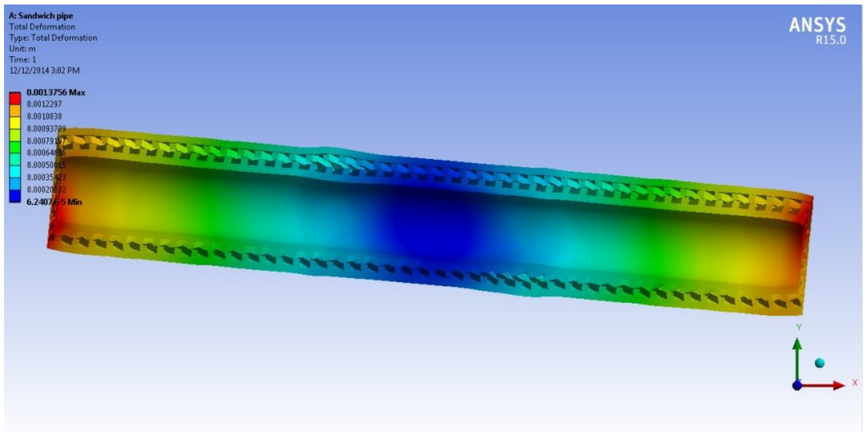


Figure 22: Total deformation of Invar pipe

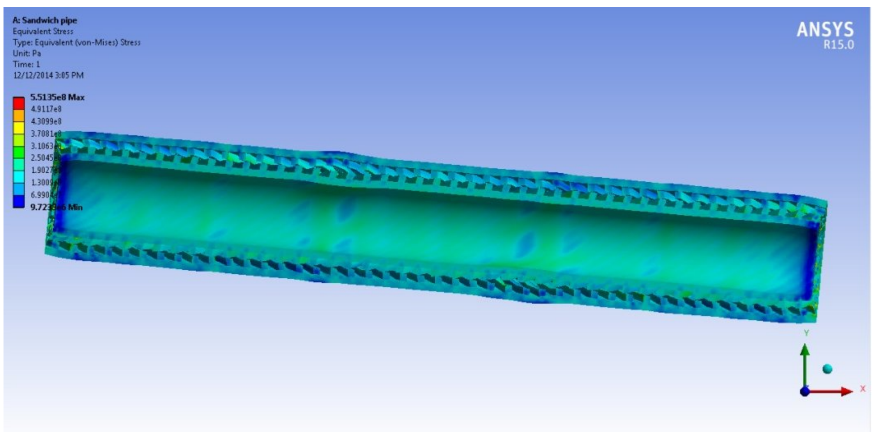


Figure 23: Stress distribution of Invar pipe

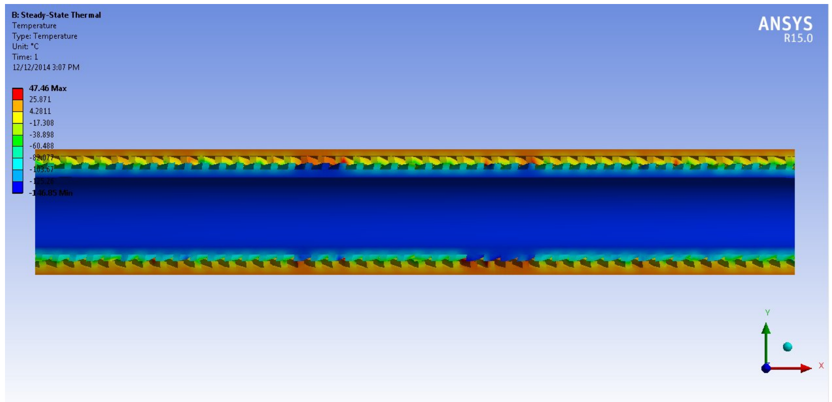


Figure 24: Temperature distribution of Invar pipe

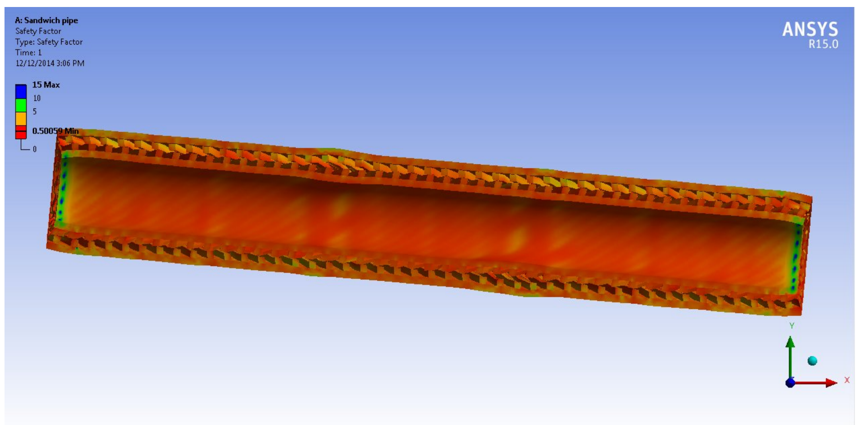


Figure 25: Safety factor distribution of Invar pipe

Table 18 below shows the overall result of Invar pipe configuration.

Table 18: Invar result

Total deformation	1.3756E-003	m
Max. strain	3.9971E-003	m/m
Max. stress	5.5135E+008	Pa
Minimum safety factor	0.50059	Pa
Maximum stress ratio	1.9977	
Maximum frictional stress	9.4339E+007	
Total heat flux	1.0563E+005	W/m^3

4.5 Discussion

4.5.1 Wall thickness

Fig. 26 shows the comparison of ASME 31.3 and ASME 31.4 standard. In LNG designing, it is much more preferable to comply with ASME 31.3 Standard due to the fact that LNG is a sensitive product that need to be handled with high safety factor. Thus a conservative calculation for wall thickness is followed as ASME 31.3 is more conservative than ASME 31.4 standard.

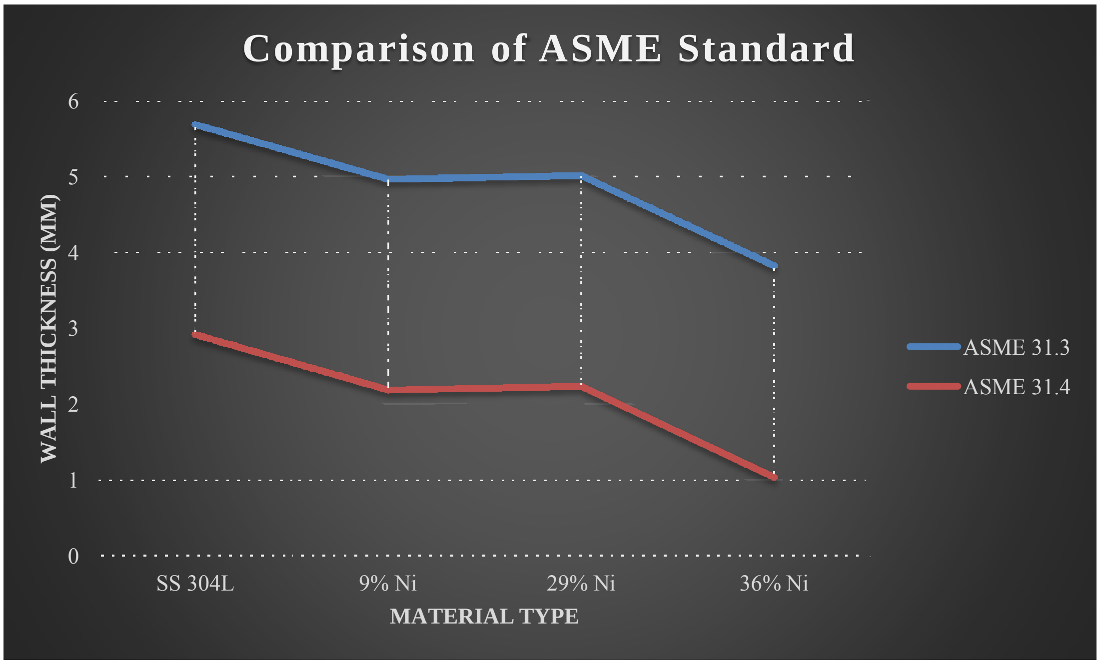


Figure 26: Comparison of ASME standards

4.5.2 Stress analysis result

Fig. 27 shows the distribution of each test result from finite element analysis with related to three materials that is being tested in this research.

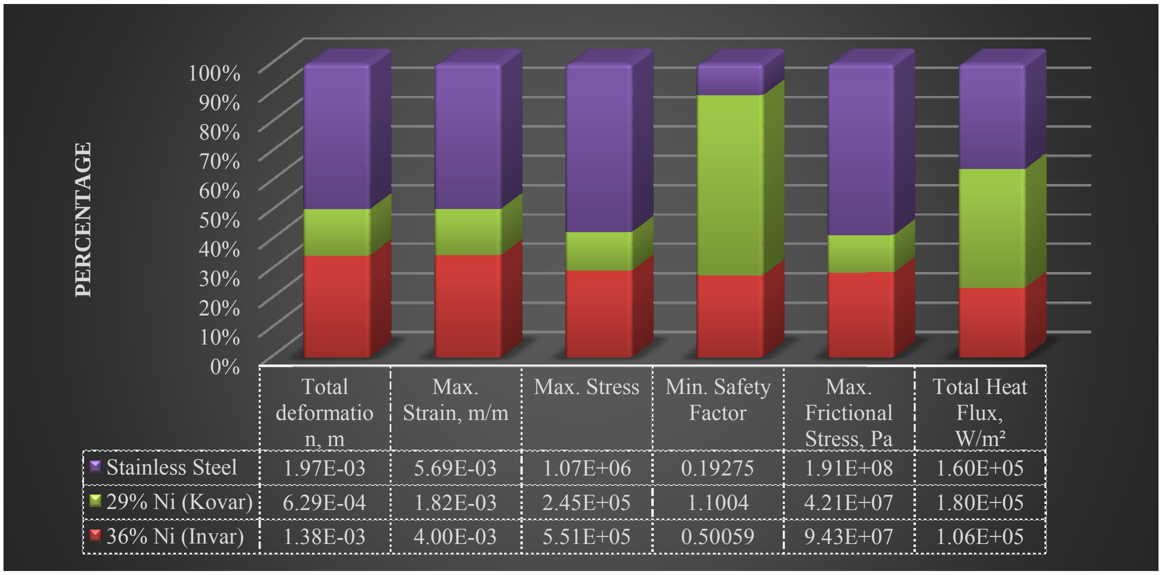


Figure 27: Test results for three materials

Total deformation and Maximum strain - Based on the result, Kovar performed better in which it deformed only by 16% (1.82E-03 m/m) compare to Invar and stainless steel. *This happened because the composition of a 29% Nickel allow it to resist more contraction in cryogenic state.*

Maximum stress – The result shows that Kovar is experiencing about 13% (2.45E+05 Pa) of stress under the operating condition.

Safety factor - Kovar have a safety factor more than 1. This shows that this material is safer to operate even if there is an unexpected increase in the internal pressure. The other two materials have SF less than 1.

Maximum frictional stress –. Based on the result, Kovar have a less frictional stress. This is due Kovar is having less deformation effect which make the material to be more stable and have less friction compare to Invar and stainless steel.

Total heat flux –From the result, it can be seen that Invar performed better as it absorb less heat energy. The lesser the heat absorbed, the lower the conduction rate of the material.

CHAPTER 5:
CONCLUSION

5.1 Conclusion

In this research, an extensive FEM simulation has been presented to aid the material structural analysis for the configuration of subsea sandwich cryogenic pipeline. Computer based simulation by using ANSYS had aided in the process of FEM analysis for three different materials namely for Stainless Steel, 29% Nickel and 36% Nickel. Equivalent Von Mises stress of the defective pipeline had been simulated and produced by using ANSYS.

The results from different analysis of three material were compared to examine the effect of cryogenic temperature under operating pressure impacted on the sandwich pipeline configuration. Among all the models, 29% Nickel alloy performed better in term of deformation, maximum stress, frictional stress, stress ratio, and safety factor.

5.2 Suggested Future Works

a) Stability considerations: subsea pipeline may become unstable for several reasons and suitable subsea configuration of pipe should be chosen to reduce any possibility of instability. Such instability should be check on local buckling of pipe, propagation buckling, and dynamic instability of pipeline under cyclic loading.

b) Fatigue consideration: Subsea pipeline subjected to wave, current and temperature variations should be investigated for fatigue analysis. Fatigue check consist of analysing the pipeline for crack and service life.

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