METAL-TO-METAL SEALING FOR HIGH PRESSURE SUBSEA PRODUCTION SYSTEM (SPS) BOLTED FLANGE CONNECTOR

By

NURUL HIDAYAH BINTI MOHAMMAD RADZI

A project dissertation submitted
in partial fulfilment of the requirements for the
Bachelor of Mechanical (Hons)
(Mechanical Engineering)

JAN 2009

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CERTIFICATION OF APPROVAL

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Approved:

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Project Supervisor

UNIVERSITI TEKNOLOGI PETRONAS
TRONOH, PERAK

Jan 2009

CERTIFICATION 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.

Nurul Hidayah Binti Mohammad Radzi

ABSTRACT

Metal to metal seal is one type of static seal used in high pressure Subsea Production System (SPS) Bolted Flange connector. Static sealing elements, as their classification implies, remain stationary relative to the surfaces they are sealing against. The subsea system can be located many miles away in deeper water and tied back to existing host facilities in shallow water. Due to the deeper water, higher challenges and problems need to be considered such as high reservoir pressures, low sea-bed temperatures, large variations in water depth range, flow assurance challenges, geo-hazard issue like gas hydrates, rough metocean condition, remoteness and hydrostatic pressure. The first objective is to analyze how leakages occur in SPS Bolted Flange connector. Bolt, flange and seal are the three main components in Bolted Flange connector that can contribute to the excessive leakage. Once excessive leakage happens in the deepwater, there will be loss in productivity, marine pollution and other important effects that need to be highly considered. From the literature reviews, main factors due to the seal that can cause leakage are inadequate overall flatness, inadequate smoothness and seal ring breakage can be concluded. The second objective is to propose and demonstrate the applicability of metal to metal sealing of SPS Bolted Flange connector for deepwater application. Temperature, pressure, industry design codes, life expectancy, leakage integrity and maintenance and accessibility are the key elements in selection of metal seal for SPS Bolted Flange connector. For this project, metal O-Ring has been chosen as the design for metal seal inside SPS Bolted Flange connector because its characteristics meet the deepwater and subsea requirements. The comparison has been made between Stainless Steel AISI 321, Alloy 600 and Alloy X750 by calculating the pressure exerted on the metal seal. All these materials satisfy subsea requirement but Stainless Steel AISI 321 has been chosen for metal O-Ring inside Bolted Flange connector due to cost consideration.

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INTRODUCTION

1.1 Background of Study

In Malaysia, the oil and gas development and production activities started its deepwater development when Kikeh, offshore Sabah was put to production in July 2007. It is in water depth of 1320 m [1]. Kikeh Development set benchmark as first deepwater development for Malaysia. The use of Dry Tree Unit (DTU) and one of the largest deepwater Floating, Production, Storage and Offloading (FPSO) facilities built by Malaysian yard. Project challenges for first SPAR to be used outside Gulf of Mexico and first SPAR to be used with tender assisted drilling rig, largest external turret, first application of mid water flowlines, subsea manufacturing and many more.

Type of facilities applicable for deepwater are subsea wells, fixed platforms, compliant towers, spars, tension leg platforms, and floating production, storage and offloading systems (FPSO's) [4]. Pipeline and flowline are among the important component in the subsea systems. Leakage can occur in any of these lines.

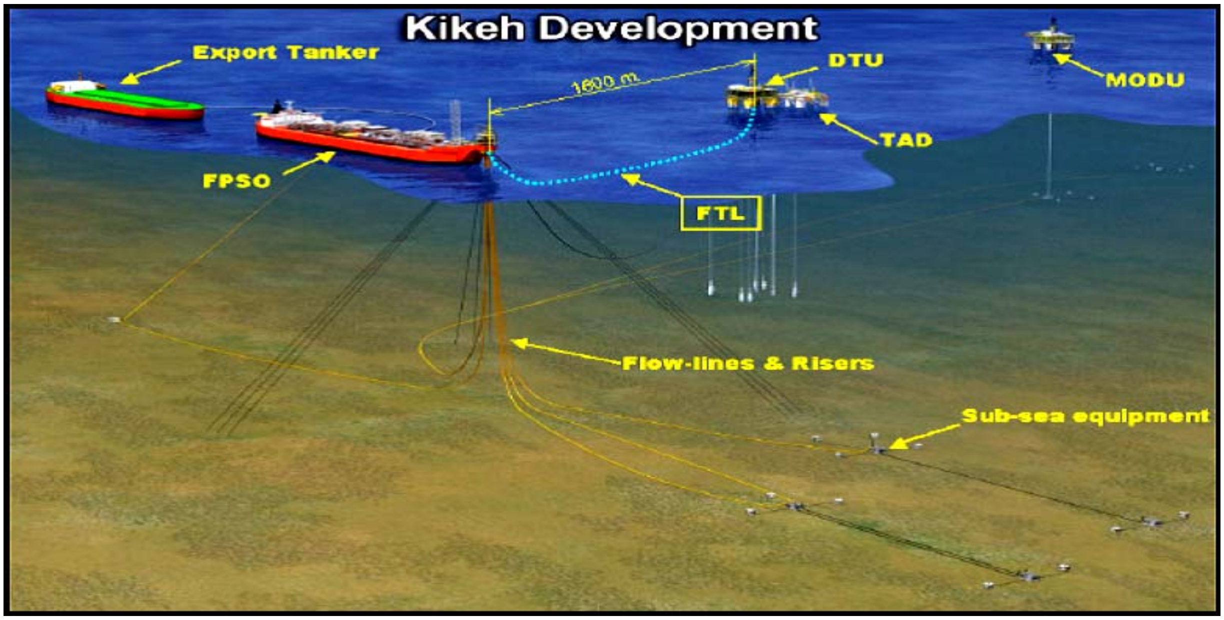


Figure 1.1: Kikeh Typical Development Scheme [1].

1.2 Problem Statement

The metal to metal sealing system will be applied for high pressure Subsea Production System (SPS) connectors. The subsea system can be located many miles away in deeper water and tied back to existing host facilities in shallow water. Due to the deeper water, higher challenges and problems need to be considered such as high reservoir pressures, low sea-bed temperatures, large variations in water depth range, flow assurance challenges, geo-hazard issue like gas hydrates, rough metocean condition, remoteness and hydrostatic pressure. Material and sealing arrangement to be used in the SPS connectors are among the important factors that need to be considered in order to encounter all of these problems. Besides, leakage can occur in any of the subsea components. In any of the lines (flowline, pipeline, umbilical), leaks in the fittings or a structural breach may be a factor. Any connection point on the manifold, termination unit, or jumper from the lines can be targeted area for leaks. Structural integrity would be another factor. Pressure drops may result in leaks in the lines, with Robot Operated Vehicle (ROV) inspection of the lines and other components capable of visually confirming the leaks. There are safety valves at the host facility and in the production tubing beneath the subsea tree that can be shut in when leak is detected to minimize the lost fluids.

1.3 Objective

The objectives of the project are:

1. To analyze how leakages occur in SPS Bolted Flange connectors leading to the study of characteristics of a good Bolted Flange connector.
2. To propose and demonstrate the applicability of metal-to-metal sealing of SPS Bolted Flange connectors for deepwater application.

1.4 Scope of Study

The scope of the project focuses on metal seal inside the Bolted Flange connector. Metal seals are manufactured from one metal or a combination of metals in a variety of shapes and sizes. High contact stress at the sealing interface is required to cause plastic flow of the metal to create seal. Metal seals also have some inherent resilience and ability to be energized by pressure. Besides, they have the greatest range of temperature and pressure of any static seal. The metal-to-metal seal relies on two metal surfaces being brought together and clamped so that any gap remaining between them is so small thus excessive leakage can be prevented.

CHAPTER 2
LITERATURE REVIEW

2.1 Deepwater Technology

By Malaysia Production Sharing Contracts (PSC) definition deepwater is anything in greater than 200 m water depth. Globally they prefer to consider deepwater for anything in greater than 400 m water depth. Ultra-deepwater is for anything in greater than 1000 m water depth [1].

In order to develop an oil/gas field in deepwater the facilities demand technology different from the conventional methods which commonly applicable for anything less than 200 m water depth. There reasons for these requirements include:

a. High reservoir pressures
b. Low sea bed temperatures
c. Flow Assurance problems
d. Geo-hazards and Structural stability
e. Extreme Met Ocean conditions

Special study need to be done before any conventional methods could be applied for deepwater facilities. The ultimate is to put facilities that fit for purpose, safe, reliable while meeting the appropriate standards and above all economically viable.

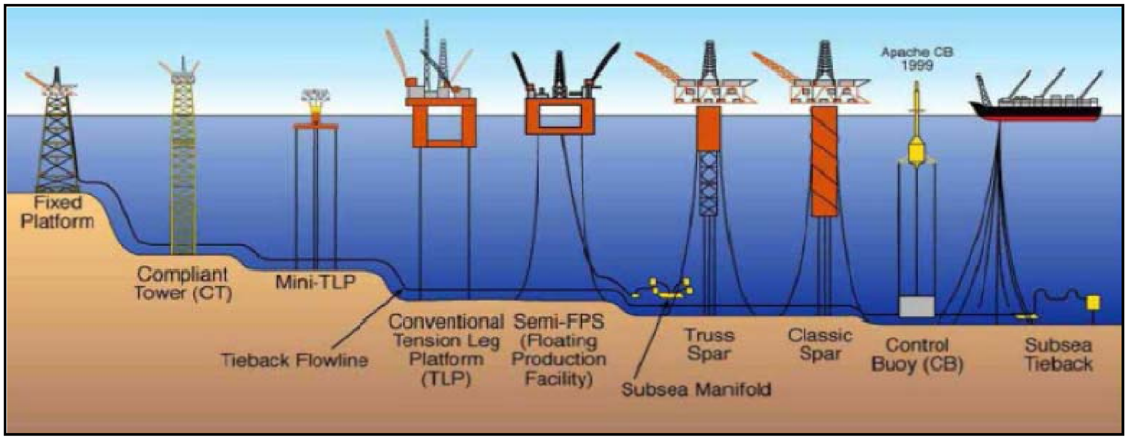


Figure 2.1: Deepwater Development Concept [2].

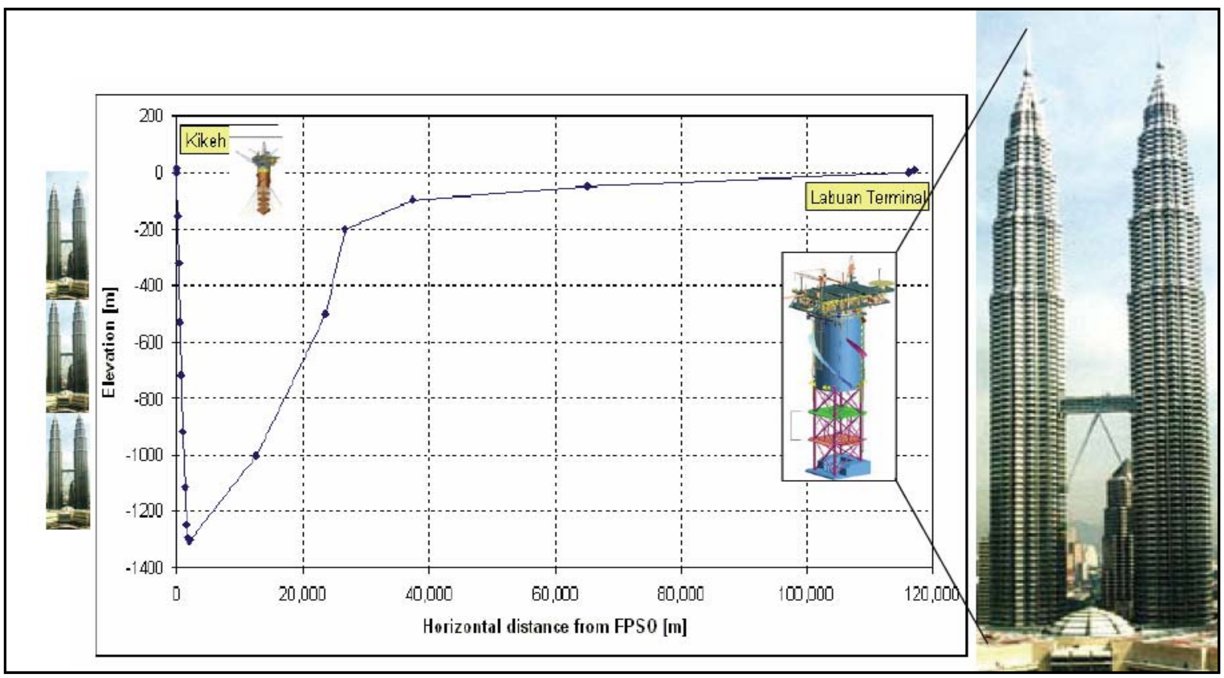


Figure 2.2: Kikeh Water Depth at 1320m is equivalent to 3 x 452m PeTT [1].

2.2 Subsea Production System (SPS)

Subsea systems are generally multicomponent seafloor systems that allow for the production of hydrocarbons in water depths that would normally rule out installing conventional fixed or bottom-founded platforms. Through an array of subsea wells, manifolds, central umbilicals and flowlines, a subsea system can be located many miles away in deeper water and tied back to existing host facilities in shallow water. Host facilities in deeper water would likely be one of several types of floating production systems [4]. Figure 2.3 shows different arrangements of the subsea system components, which can be described as

a) Single-well satellite
b) Multiwell satellite
c) Cluster-well system
d) Template
e) Combination of the above

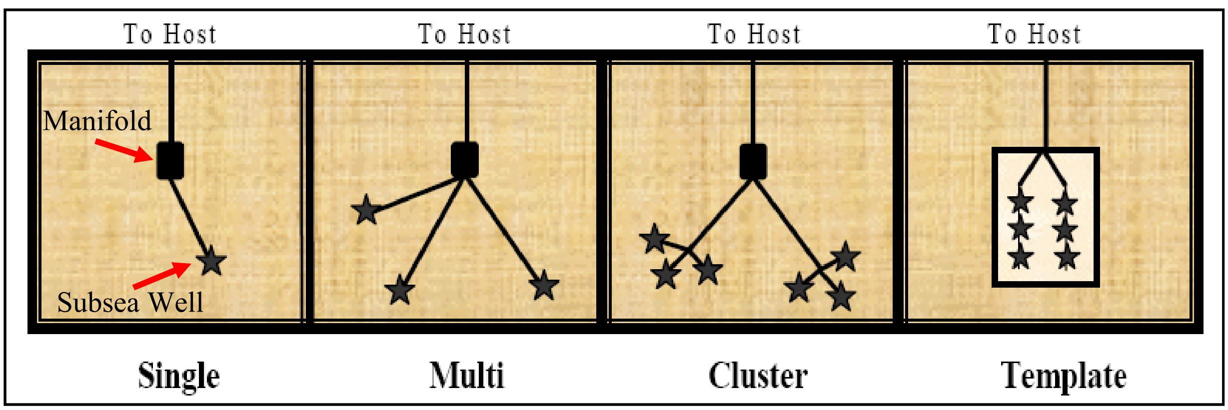


Figure 2.3: Various layouts of the subsea components [4].

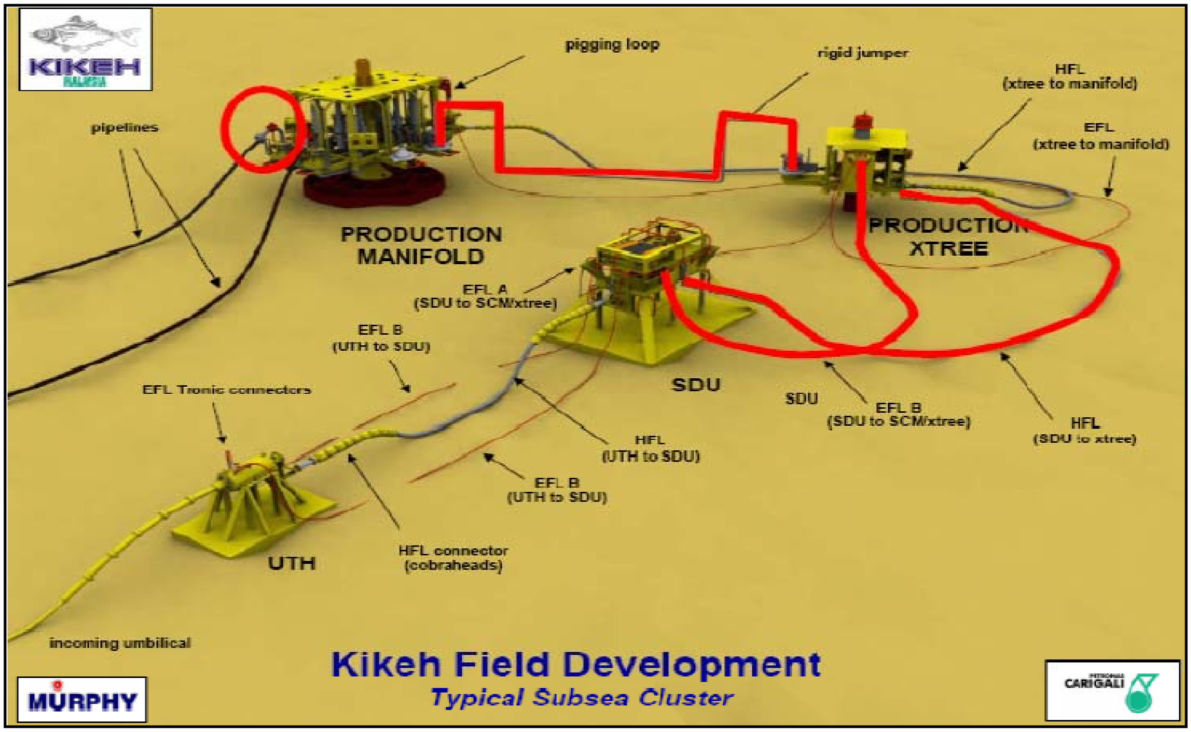


Figure 2.4: Typical Subsea Cluster of Kikeh Filed Development [25].

2.3 The Evolution of Sealing Technology

Thirty years ago, achieving a minimum leak rate was far from being the primary concern of the sealing industry. The purpose of sealing mostly about trying to meet operational requirements and reach acceptable system efficiency since the start of industrial era [6].

As systems evolved and due to high demands in pressure, safety became a major issue, leading to the implementation of codes and standards as we know them today. But sealing issues, typically on bolted flanges always became a second concern. At the design stage, the seal or gasket would remain a black spot on the assembly drawing, and would only be specified at the final stages against vaguely defined gasket mechanical characteristics.

Non-metal-to-metal or ‘elastomeric’ concept and gasket or ‘O’ ring are the example of static seals. The gasket or ‘O’ ring is the oldest static seal. The more load or pressure exerted on one given interface, the more plastic deformation occurs that fills surface defects, preventing fluids passing through the interface. The gasket is designed to take all of the plastic deformation needed, rather than the joint faces. Limitations in this sealing principle are continually being addressed as sealing material evolves.

During this time, the mechanical integrity of the system becomes the highest concern instead of maintaining the leak-tightness and all existing codes and standards around the world were built on that basis. A combination of several process requirements created new demands – nuclear power generation, high technology systems using ultra-high vacuum (UHV), exploration of oil and gas to the deeper sea and extreme pressures and temperatures, and environmental awareness caused the trend to change.

The development of metal-to-metal system over the past 30 years has revealed the non-metal-to-metal seals limitations. However, there's a lot of unanswered question for the metal-to-metal applications [6].

2.4 Subsea connectors

Connectors are used to make a tight connection between two fluid carrying elements. Most of the fluid is carried under high pressure, and /or high temperature. The connection may also be exposed to high external loads and /or pressure as a result of the deep water depth.

2.4.1 Bolted flange connection

Bolted flange connections of metal-to-metal contact type (MMC) are frequently used in industrial plants. Different from floating type flanged joints, where the total bolt load is transmitted through the gasket, only that part of the bolt is taken over by the gasket which is necessary for MMC, as shown in Figure 2.5. The additional bolt load, transmitted to the flange-flange contact, has to compensate for the unloading effects in service due to internal pressure, external loadings, etc., in order to avoid a loss of MMC. Obviously, the bolt load for MMC should be as low as possible.

The main advantages of MMC flanged joints are [17]

- High stiffness due to the restricted deformation of the flanges
- No change of gasket stress with external loadings
- Well defined reproducible thickness of the gasket after assembly

In view of these facts MMC joints are mainly used where large bending moments or transient loadings (vibrations, pressure fluctuation) are expected. In valves the constant gasket thickness is of importance for the function [17]. As an example the gasket thickness influences the flow rate in safety valves.

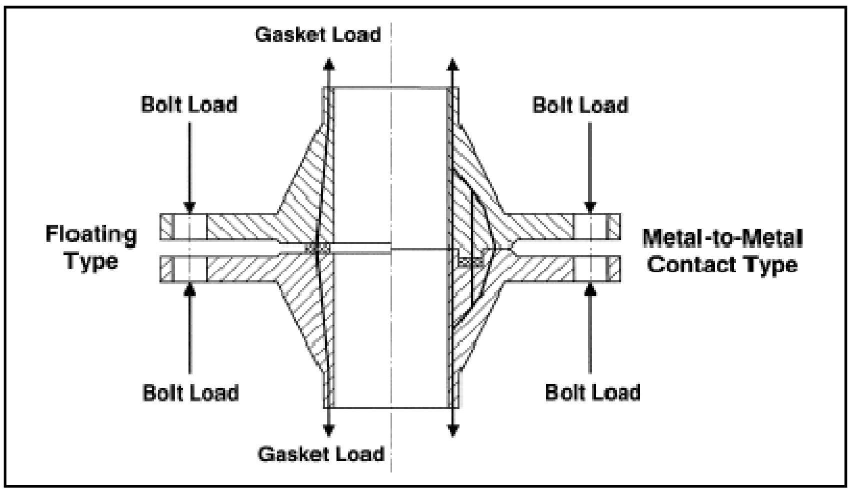


Figure 2.5: Bolted flange connections of floating (left) and MMC type (right) flanged joints (schematic) [17].

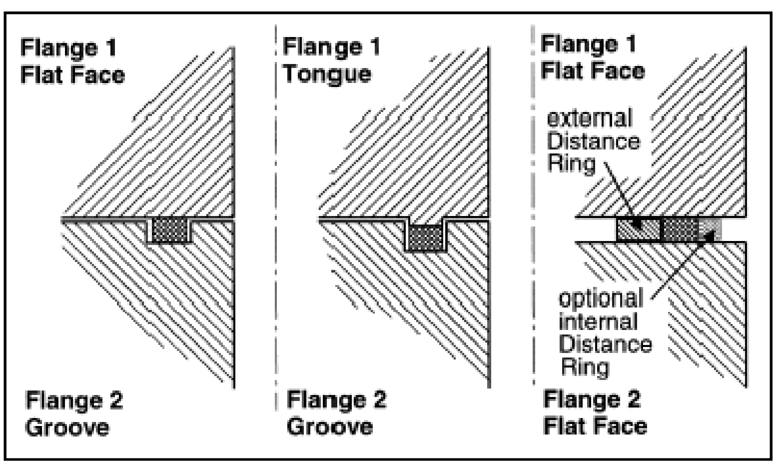


Figure 2.6: Assembly situation of gaskets in MMC type flanged joints (schematic) [17].

2.4.2 *Non-integral pipeline collet connector*

The 12”-non-integral pipeline collet connector join a 12”-pipeline with an offshore platform riser. The function of this joint is to seal the two extremity of the pipe by using a locking ring that slides pushed by hydraulic jacks; this movement causes the sliding of 12 fingers that allows the pipes to contact [16].

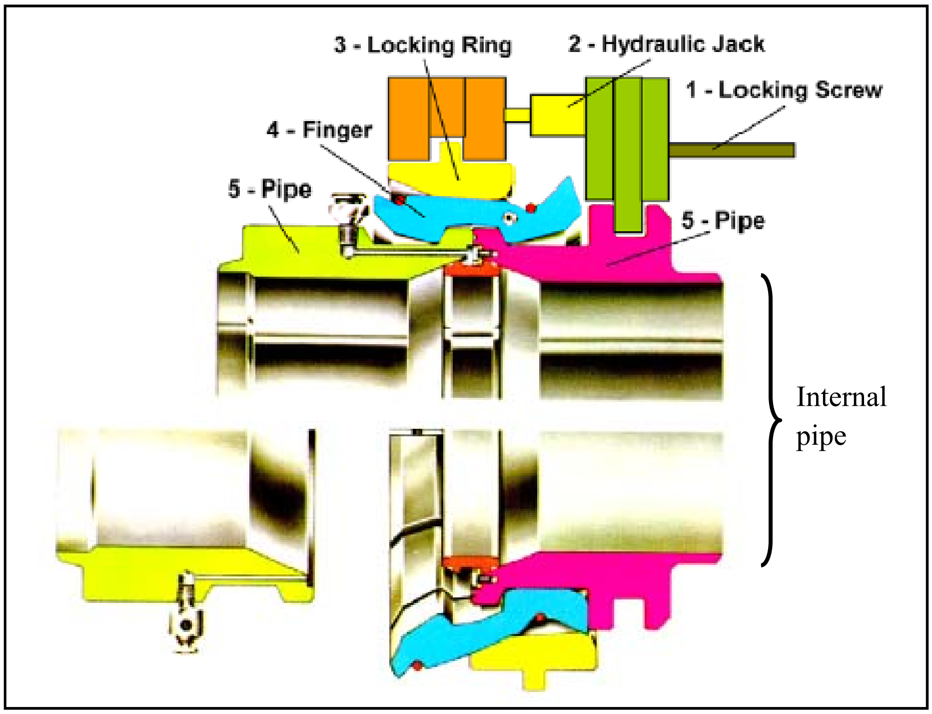


Figure 2.7: Scheme of the non-integral connector [16].

In Figure 2.7, the scheme of a 12”-non-integral collet connector is shown. By means of this picture, it is possible to figure out how the collet works: a torque, applied by the locking screw (1), allows the hydraulic jack (2) to push the locking ring (3) which slides slightly. This latter movement causes sliding and small rotation of 12 (circumferentially placed) fingers (4) that allows to contact and to seal the two mating extremities of the pipes (5). In Table 2.1, Figure 2.8 and Figure 2.9, some details about the characteristics of the analyzed connector are shown.

Table 2.1: Main characteristic of the 12”-non-integral collet connector [16].

Characteristics	Parameter	Value
Geometry	Nominal diameter	304.8 mm
	Outer diameter	323.8 mm
Operating condition	Pressure IN	1.4 - 2.4 MPa
	Pressure OUT	1.2 MPa
Make-up torque	6013 Nm	

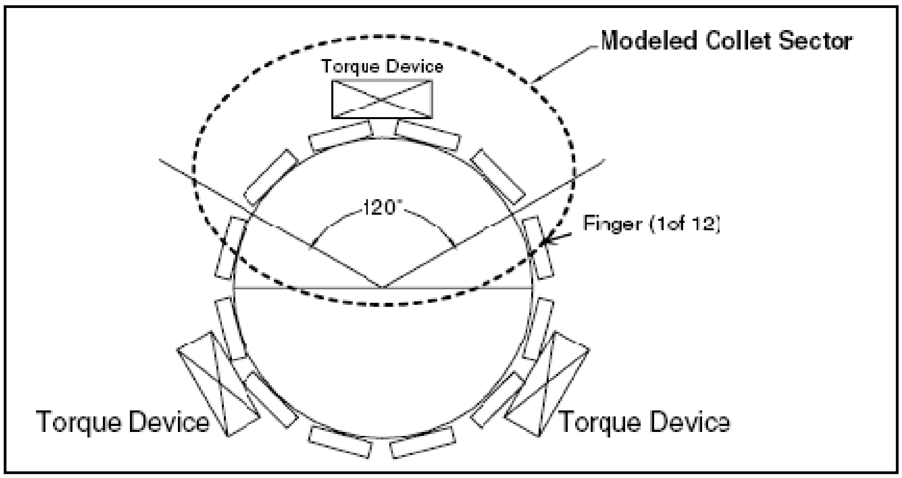


Figure 2.8: Sketch of the geometric and load symmetries in the non-integral connector [16].

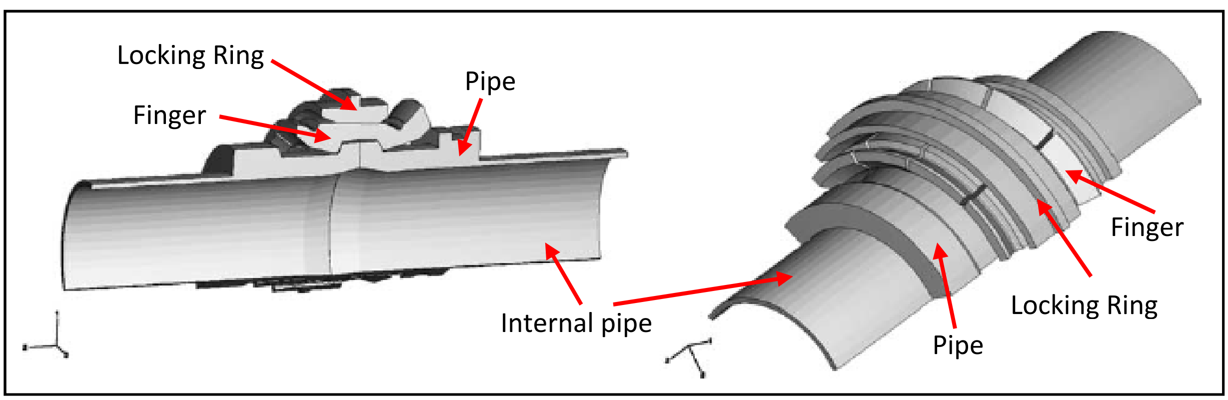


Figure 2.9: The geometry of the FE model from two different viewing points [16].

2.4.3 Deep water sealine connector

The geometric characteristics of the 20in. threaded connector for deep water J-pipe lay are described in Figure 2.10. The main parts of the joint are: the pin (1), the box (2) and the flange (3). The sealing area, described in Figure 2.11, consists of a radial metal ring (A) and a second metal area (B) on a cone surface ledge (C) on the box. Ring (A) reaches the yield stress by screwing the pin into the box. The plasticization of the metal ring (A) on the pin on the ledge (C) of the box guarantees the zero leakage of the connector. The second metal area (B) contacts the ledge (C) after the ring (A) radial strain (R) has occurred; so, the loads that are superimposed after the make-up of the connector do not increase the plastic permanent strains of the ring (A) because of the presence of the metal area (B). The flange has a double function: to resist the torque moment and to act as reinforcement ring against the internal pressure action. This means that it has to prevent the relative displacements between the pin and the box. The cylindrical threaded surfaces are on two diameters and transmit the axial stress between the pin and the box; the shape and dimensions of the threads have been determined in order to obtain the required stiffness ratio between the different parts of the connector. The material is steel API 5LX X65 with yield strength $\sigma_y = 0.457 kN/mm^2$ [9].

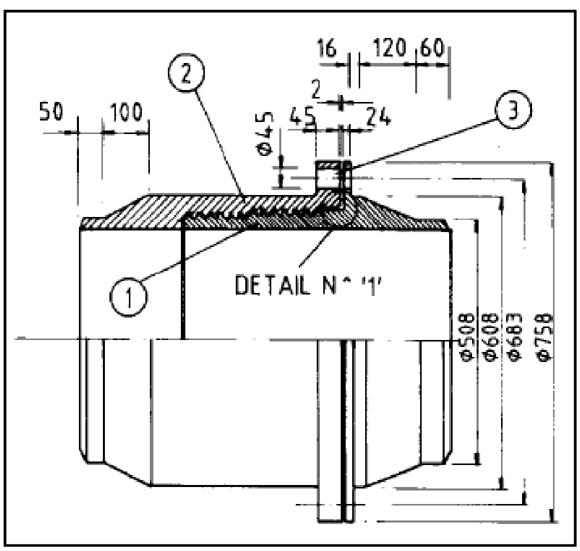


Figure 2.10: Sealine mechanical connector [9].

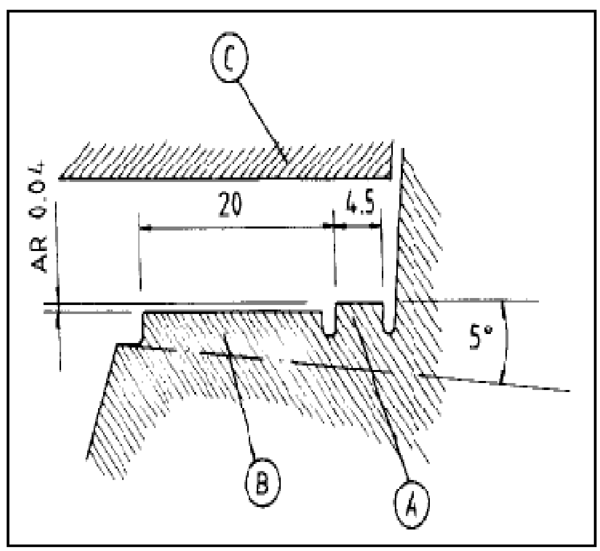


Figure 2.11: Sealine mechanical connector: detail (1) [9].

2.4.4 FMC Connector

These connector manufactured from FMC Technologies company.

2.4.4.1 FMC KC-Collect Connector

The KC Collet Connector has been designed for connection of subsea flowlines, risers and XT-wing hubs, to the different parts of the subsea production systems. These may be connected horizontally or vertically. The connectors can be fitted with several bore configurations, from the nominal full-bore, to smaller mono-bore and multi-bore versions, including umbilicals. Connectors are made up by either internal hydraulic operation, or by an external Connector activating tool (CAT), leaving no hydraulic components subsea [11].

Figure 2.12: KC-4 Collet Connector [11].

Figure 2.13: KC-4 Multibore Collet Connector [11].

2.4.4.2 FMC KL-Clamp Connector

Clamp Connectors are based on a 2 segmented clamp screwed together around two hubs. Clamp connectors may connect both single and multi-bore connections, and are mainly used in horizontal applications [11].

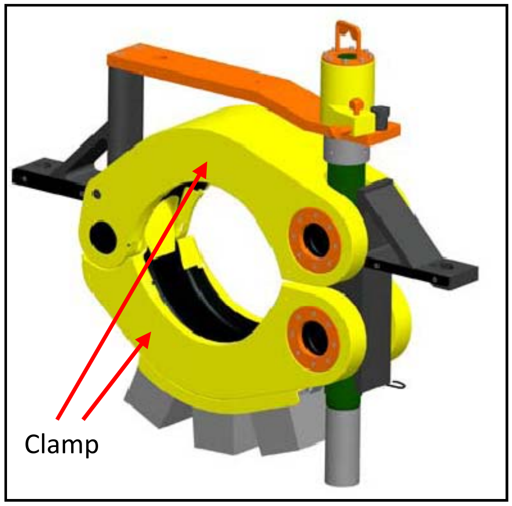


Figure 2.14: KL Clamp Connector [11].

2.4.4.3 KX Gasket

FMC KC and KL connectors are using the KX metal to metal seal. The seal is made of Inconel 625, and is Silver Plated. This provides a gas tight seal, and is suitable for single and multibore Connections. The KX gasket is of a flexible design, allowing for compensation of fabrication tolerances and misalignments. In case of damage to the primary sealing area in the hubface, the KX-design provides a back-up seal by utilizing a different area in the sealface. The seal design is equipped for back seat (external seal) test after connection to verify proper connection option [11].

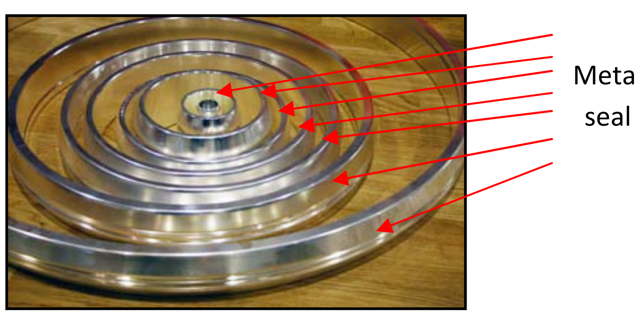


Figure 2.15: KX Gasket [11].

CHAPTER 3
METHODOLOGY

3.1 Project Flow

The flow chart below shows the sequence of the basic steps required to ensure the continuity of the project for a year:

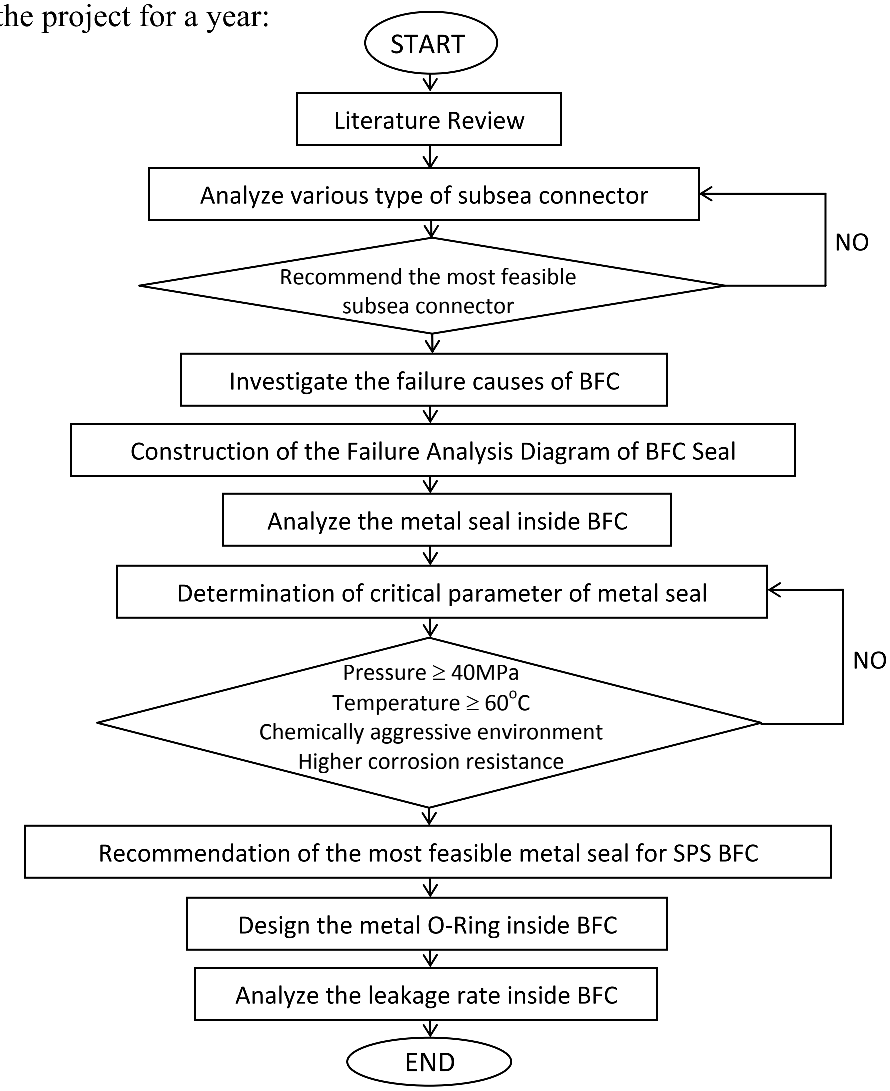


Figure 3.1: Flow chart of the project.

3.2 Gantt Chart

The Gantt chart below shows the planning and flow for first and final semester of final year project:

Table 3.1: Gantt chart for first and second semester planning.

No	Details/ Week	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
	FIRST SEMESTER																
1	**LITERATURE REVIEW**	■	■	■	■	■	■	■	■	■	■						
2	**INVESTIGATE THE FAILURE CAUSES OF BOLTED FLANGE CONNECTOR (BFC)**						■	■	■	■	■						
3	**CONSTRUCTION OF THE FAILURE ANALYSIS DIAGRAM OF BFC SEAL**												■	■	■	■	■
	SECOND SEMESTER											**Midsemester break**					
4	**ANALYZE THE METAL SEAL INSIDE BFC**	■	■	■													
5	**DETERMINATION OF CRITICAL PARAMETER OF METAL SEAL**				■	■	■										
6	**RECOMMENDATION OF THE MOST FEASIBLE METAL SEAL FOR SPS BFC**							■	■	■	■						
7	**DESIGN THE METAL O-RING INSIDE BFC**												■	■			
8	**ANALYZE THE LEAKAGE RATE INSIDE BFC**														■	■	■

3.3 Technique of Analysis

3.3.1 Literature Review

During this phase, resources are very important in order to get start of the project. Studies about Deepwater technology, Subsea production system (SPS), Subsea connectors and Metal-to-metal sealing need to be done before proceed to the next step. This is to ensure the project can be logically being developed regarding to its requirements and the resources.

Information from books, journal, focal person and internet are very useful for references thus it will be the major sources of information on developing this half of the project.

3.3.1.1 Failure Statistics

Figure 3.2, Figure 3.3 and Table 3.2 show some of the statistical data of pipeline failures and spills in Pacific Region and Gulf of Mexico (GOM) Region.

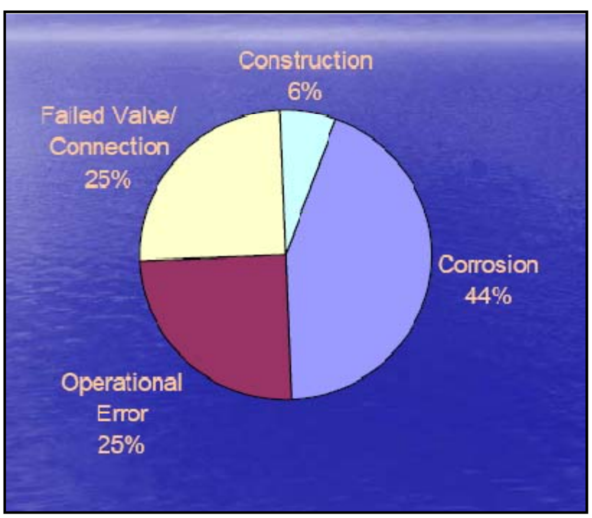


Figure 3.2: Cause of Pipelines Failure in Pacific Region in last 12 years [24].

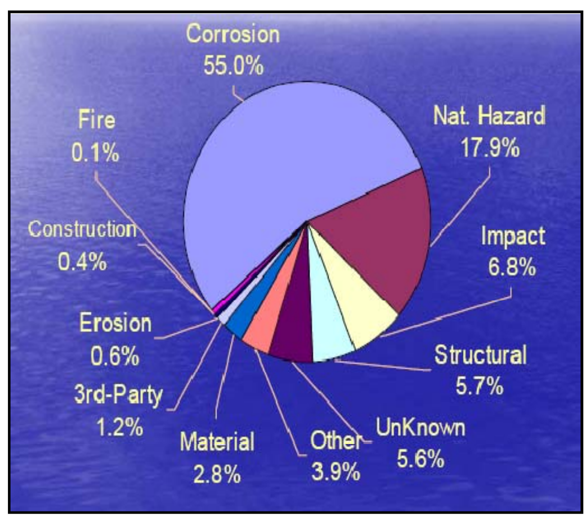


Figure 3.3: Cause of Pipelines Failure in GOM Region (not including 2005) [24].

Table 3.2: Pipeline Hydrocarbon Spill Statistics by Cause in GOM from 1972 - 2006 [23].

CAUSE CLASSIFICATION	Small and Medium Spills 50-999 bbl				Large and Huge Spills >=1000 bbl			
	HIST. DISTRIBUTION %	NUMBER OF SPILLS	EXPOSURE [km-years]	FREQUENCY spill per 10^5km -year	HIST. DISTRIBUTION %	NUMBER OF SPILLS	EXPOSURE [km-years]	FREQUENCY spill per 10^5km -year
CORROSION	8.57	3		1.0955	6.67	1		0.3652
External	2.86	1		0.3652				
Internal	5.71	2		0.7303	6.67	1		0.3652
THIRD PARTY IMPACT	22.86	8		2.9213	66.67	10		3.6517
Anchor Impact	20.00	7		2.5562	33.33	5		1.8258
Jackup Rig or Spud Barge					6.67	1		0.3652
Trawl/Fishing Net	2.86	1		0.0365	26.67	4		1.4607
OPERATION IMPACT	8.57	3		1.0955	6.67	1		0.3652
Rig Anchoring	2.86	1		0.3652				
Work Boat Anchoring	5.71	2		0.7303	6.67	1		0.3652
MECHANICAL	5.71	2		0.7303				
Connection Failure	2.86	1	273847	0.3652			273847	
Material Failure	2.86	1		0.3652				
NATURAL HAZARD	43.57	17		6.2078	20.00	3		1.0955
Mud Slide	5.71	2		0.7303	6.67	1		0.3652
Storm/ Hurricane	42.86	15		5.4775	13.33	2		0.7303
ARCTIC								
Ice Gouging								
Strudel Scour								
Upheaval Bucking								
Thaw Settlement								
Other Arctic								
UNKNOWN	5.71	2		0.7303				
TOTALS	100.00	35		12.7809	100.00	15		5.4775

3.3.1.2 Selection of SPS Connector

The comparison between all of these connectors has been made based on the literature review before choosing the best and the most commercial one. Bolted Flange Connector has been chosen because it is the most common type of connector due to its reliability, less maintenance (nearly zero because of the non moving parts), adaptability, availability (shorter delivery period, many suppliers, etc) and simplicity [22]. Besides, these types of connections are still an integral part of offshore developments for ease of assembly and construction [14].

The characteristics of Bolted Flange Connector (BFC) that made it been selected instead of other connectors are [26]:

- It is the most field proven connection system and has been extensively used in the industry for subsea gas pipeline.
- The bolted flange offer also the most tolerant connection with regard to stress in the system and long term reliability and is also least subject to damage for future disconnection and reconnection.
- It offers minimum interference with the laying operations and installation of specialized equipment.
- The interface is limited to welding a weld neck flange to the pipeline and use of conventional and standard bolt torque equipment offshore.
- The ANSI flange is a cost effective pipeline connection system.

Location of the BFC in the subsea production system shown in Figure 3.4 below:

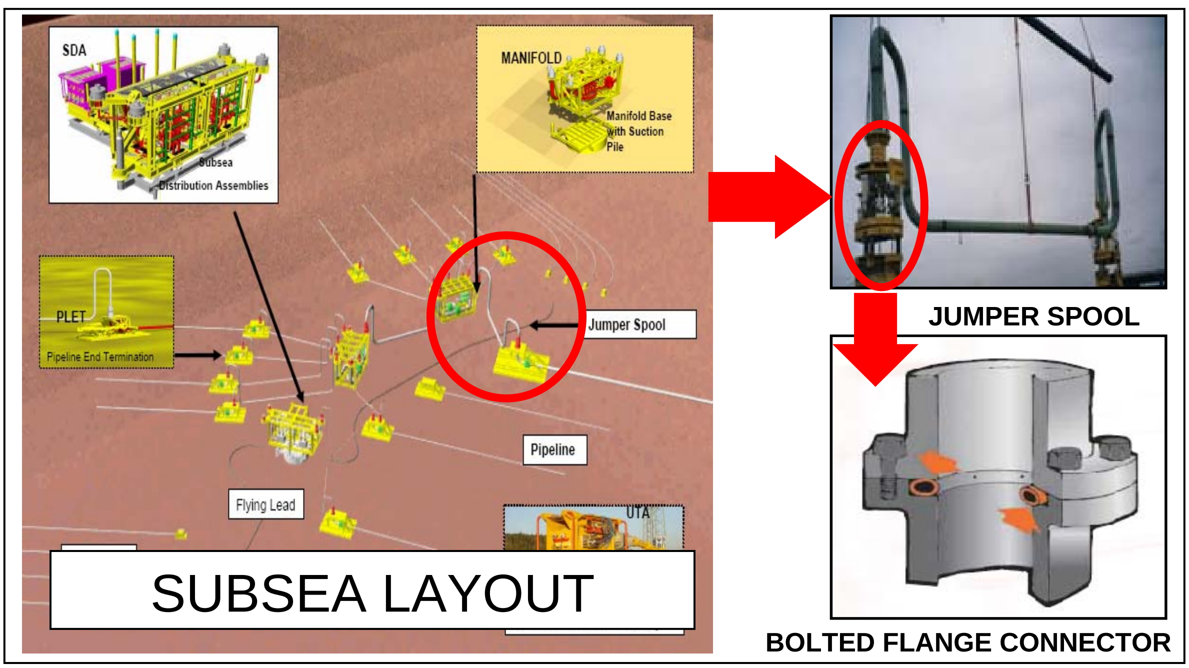


Figure 3.4: Location of Bolted Flange Connector in Subsea Production System.

3.3.2 Investigation of BFC Failure Causes

Despite dramatic advances in subsea engineering capabilities, the pressures and temperatures in increased water depths create an environment that's highly conducive to leakage. During the life of a subsea system, leaks can occur in most of its components. The components for Bolted Flange connector shown in Figure 3.5.

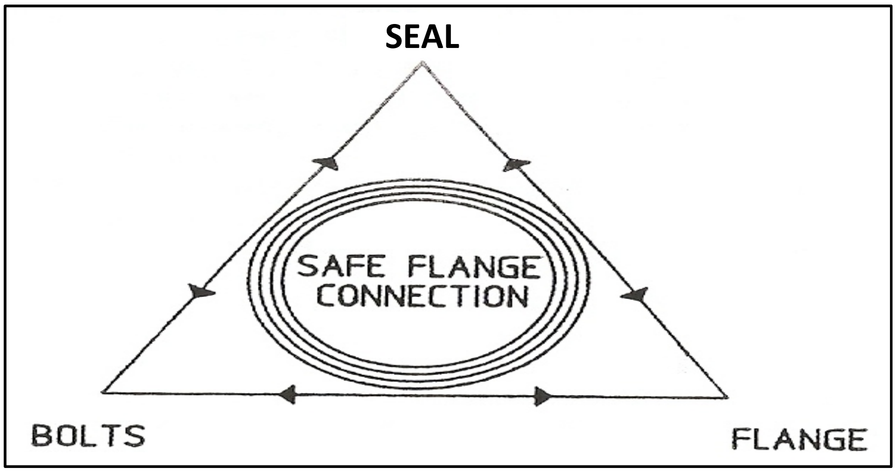


Figure 3.5: Components of a safe flange connection [18].

A gasket is a material or combination of materials clamped between two separable members of a mechanical joint. Its function is to affect a seal between the members (flanges) and maintain the seal for a prolonged period of time. The gasket must be capable of sealing the mating surface, impervious and resistant to medium being sealed, and able to withstand the application temperature and pressure. Figure 3.6 below depicts the nomenclature associated with gasketed joint.

The gasket and the joint must be considered together. The gasket may work or fail according to whether the joint is designed in accordance with the properties of the gasket itself. Therefore, the system must be considered as a whole to determine sealing performance.

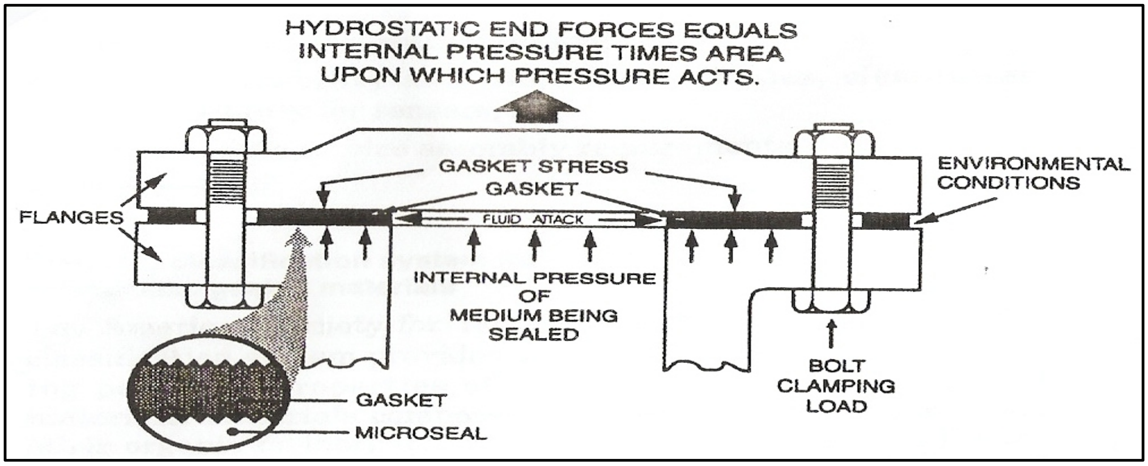


Figure 3.6: Bolted Flange Connector joint [19].

All of the known causes and contributing factors to bolted flange connector failure were obtained from the literature and experiences cited are summarized here in Table 3.3, Table 3.4 and Table 3.5 [10-19].

Table 3.3: Flange Failures.

Flange failures	
Causes	
1	Bad surface finish of flange contact faces
2	Flange rotation
3	Uneven, dirty, damaged, corroded flange
4	Weak flange arrangement
5	Creep
6	Fatigue
7	Different thermal expansion cause flange deflection
8	High static and dynamic load
9	Chemically aggressive environment
10	Environmentally assisted cracking (EAC): • Stress corrosion cracking (SCC) • Hydrogen embrittlement (HE) • Sustained load cracking (SLC)
11	Corrosion
12	Crack due to material defect
13	Bad weather
14	Improper design
15	Impact damage from: • Anchoring vessel • Fishing gear • Dropped object

Table 3.4: Bolt Failures.

Bolt failures	
	Causes
1	Poor bolting arrangement
2	Creep
3	Fatigue
4	Different thermal expansion cause bolt to stretch
5	Chemically aggressive environment
6	Environmentally assisted cracking (EAC): • Stress corrosion cracking (SCC) • Hydrogen embrittlement (HE) • Sustained load cracking (SLC)
7	Corrosion
8	Decay of marine growth
9	Impact damage from: • Anchoring vessel • Fishing gear • Dropped object
10	Improper design • Incorrect quality of bolt
11	Bad weather
12	Crack due to material defect
13	Bolt load problems: • Uneven • Insufficient • Excessive
14	High static and dynamic load
15	Precipitation hardened

Table 3.5: Seal Failures.

Seal/ Gasket failures	
	Causes
1	Improper design • Incorrect dimension • Unsuitable gasket thickness • Incorrect selection • Unsuitable initial seating stress (y) • Too little residual stress (m) • Unsuitable permeability of gasket • Incompatibility between gasket material and medium
2	Overload • Dynamic impact on the gasket

3	Incorrect installation • Misalignment of the gasket
4	Misused of bolt lubricant and adhesive
5	Aging/ long term behavior
6	Defect in the gasket
7	Creep
8	Fatigue
9	Different thermal expansion
10	Wear/erosion due to thermal
11	Improper use
12	Bad metal finish
13	Vibration
14	Crevice corrosion

3.3.3 Determination of Critical Parameter of Metal Seal

Several important criteria must be considered to achieve an optimum selection. The primary factors [12] to be considered are:

- Temperature
- Pressure
- Industry design codes
- Life expectancy
- Leakage integrity
- Maintenance and accessibility

3.3.3.1 Temperature

Temperature is a starting point that defines which materials may be considered for the application. The whole life cycle temperature range must be considered. Excursion outside the working temperature range for a material may cause temporary leakage, damage leading to significant reduction in seal life or in some cases gross failure.

Metal seals cover the temperature from cryogenic to 850^{o}C. Actual temperature limits will depend on the metal and also seal section. The highest temperatures require materials with good high temperature strength such as high nickel alloys. N06600 is used for the highest temperature metal O-Rings [12].

3.3.3.2 Pressure

The limit of pressure capability is a function of a combination of seal design and hardware arrangement.

Metal seal can be used for very high pressures, up to 3000 bar, but it is necessary to select the correct geometry [12]. Vented O-rings, or spring energized metal rings, which are also open to the pressure, are preferred. These designs will continue to be energized by the system pressure as it increases.

3.3.3.3 Industry design codes

The starting point for seal selection in many industries will be any relevant established design codes [12].

a) Gasket dimensions
   EN 12560-5: Flanges and their joints. Gaskets for class-designated flanges. Metallic ring joint gaskets for use with steel flanges.

b) Design rules
   EN 1591-1: Flanges and their joints. Design rules for gasketed circular flange connections. Calculation method.

   EN 1591-2: Flanges and their joints. Design rules for gasketed circular flange connections. Part 2. Gasket parameters.

c) Flange dimensions
   EN 1759-1: Flanges and their joints. Circular flanges for pipes, valves, fittings and accessories, class-designated. Steel flanges, NPS ½ to 24.

   ISO 15838: Ships and marine technology. Fittings for use with gasketed mechanical couplings used in piping applications. Performance specification.

   ASME B16.5: Pipe flanges and flange fittings NPS ½ through NPS 24 metric/ inch standard.

   ASME B16.47: Large Diameter Steel Flanges (26 to 60 inches).

3.3.3.4 Life expectancy

The life expectancy of metal seal directly related to the operating temperature. The temperature should be below the recommendation limit for good reliability and long life of the seal.

3.3.3.5 Leakage integrity

For very high integrity and minimum vapour transmission, it will be necessary to consider [12]:

- Permeation through the sealing material
- Interstitial leakage around the seal through the surface texture interface between sealing material and the counter-face.

Many metal-to-metal seals will not pass a stringent leak test with gas. Specialist designs of spring energized metal seals probably provide the highest leakage integrity.

3.3.3.6 Maintenance and accessibility

Component is considered to be sealed for life; manufacturing considerations are the highest priority to avoid potential maintenance. Potential sharp edges, working environment, ability to ensure seal remains in place during assembly, requirement for special tools for assembly all need to be considered. Seals that may damage the counter-face, such as due to corrosion, or metal seals causing a witness mark on the counter-face should be avoided.

3.3.4 Recommendation of the Most Feasible Metal Seal for SPS BFC

3.3.4.1 Deepwater and Subsea Requirement

All the data below were based on Kikeh field in offshore Sabah [27]:

- Ambient Temperature = 3 - 4^{o}C
- Maximum design temperature in the gas pipeline = 60^{o}C
- Internal design pressure in the gas pipeline = 5200 psig = 35.954MPa
- External Pressure [1]:

$$P_{h=1320} = h \times \rho \times g = 1320 \times 1030 \times 9.81$$
$$= 13.338 \times 10^{6} Pa = 13.338 MPa$$

- Higher corrosion resistance
- Chemically aggressive environment

3.3.4.2 Metal O-Ring

Metal O-Rings are one type of metal seals. They are designed for extreme conditions that exceed the capabilities of elastomer and plastic seals. They can be used from cryogenic temperatures up to 850^{o}C [12]. They have the benefits of being radiant tolerant and not outgassing under high vacuum. They are therefore used in applications such as nuclear power plant, high vacuum systems, gas turbines, oil and gas plants and as cylinder head and exhaust seals. They are only suitable for flange applications. The usual materials are stainless steel, Inconel or copper, depending on the application. The rings are manufactured from tube, but can be solid. The tube may be gas filled or can be of vented design [12].

Metal O-Rings depend on elastic deformation to create the sealing force. They do exhibit some elastic recovery when dismantled, but this is not considered to permit reuse. The metal thickness will be between 0.25 and 0.4 mm thickness for small cross-sections and 0.5 and 1.25 mm for seals of 6 mm cross-section. They are also often coated in a softer material that will yield and flow into the surface texture of the groove on assembly to provide improved sealing contact. The coating can be a soft metal such as silver, nickel or plastic, usually PTFE. The coating will flow when the seal is assembled and not contribute directly to the sealing stress

[12]. Figure 3.7 shows various of metal O-Ring types while Figure 3.8 shows the comparison of groove design and assembly forces between elastomer and metal O-Rings.

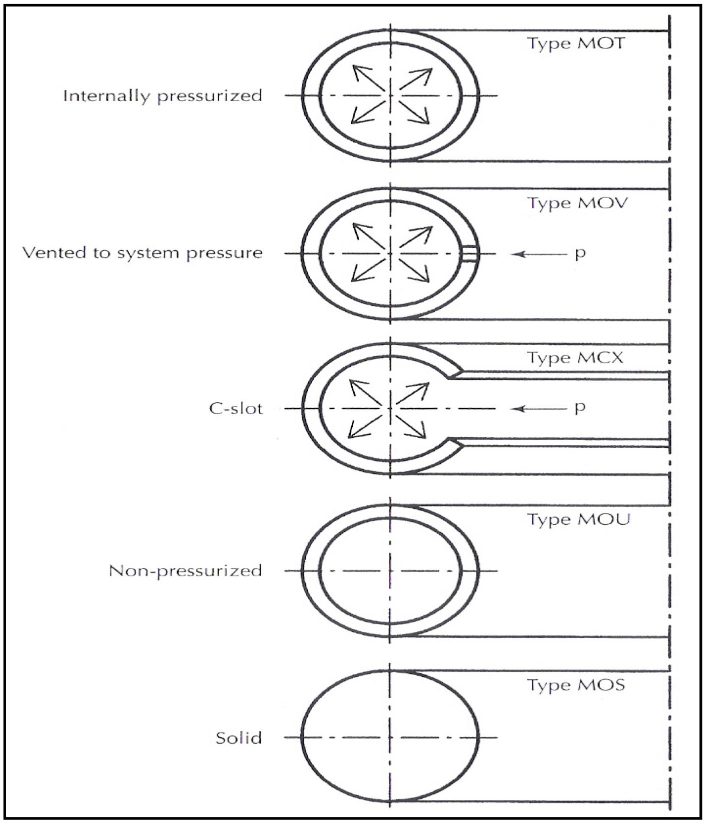


Figure 3.7: Metal O-Ring types [12].

	Metal	Elastomer
Tolerance on groove depth (*h*)	0.08 mm	0.25 mm
Tolerance on groove outside diameter (*D*)	0.05 mm	0.5 mm
Flange load to compress seal	10 000–50 000 N	150–800 N
Surface finish	0.4 μm Ra	0.8 μm Ra

For 50 mm o.d. seal of 2.5 mm section

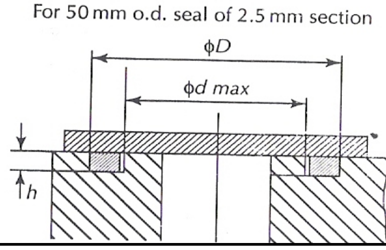


Figure 3.8: Comparison of groove design and assembly forces for elastomer and metal O-Rings [12].

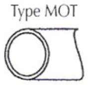
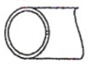
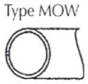
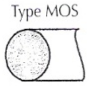
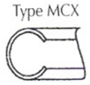
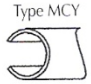
Metal O–Ring has been chosen as the design for the metal seal because its characteristics meet the deepwater and subsea requirement.

Table 3.6: Metal O-Ring specification.

	Subsea requirements (Kikeh filed)	**Metal O-ring [28]**
1	Internal design pressure in the gas pipeline = 5200 psig = 35.954MPa	Resist pressures up to 4100 bar = 410MPa
2	Maximum design temperature in the gas pipeline = 60^oC	Wide temperature range, from cryogenic to + 982°C
3	Chemically aggressive environment	Can be used in aggressive fluids
4	Higher corrosion resistance	Corrosion-resistant: not corrode and are not damaged by radioactivity
5		Highly durable and reliable in service - do not degrade in use or during storage
6		Adaptable to majority of standard flanges

3.3.5 Design of Metal O-Ring inside BFC

Based on Figure 3.9, metal O-Ring type MOT has been chosen because it is the most feasible seal for SPS Bolted Flange connector. MOT has excellent properties for extreme condition and vacuum sealing even though the seating loads and spring back properties are just satisfactory. The pressure is 40 MPa and maximum working temperature is from cryogenic to 850^oC. The standard material to be used for metal O-Ring is discussed in the result chapter. Pressure filled MOT contain a gas at 40 bar more. The pressure of this gas increases at higher temperatures, compensating for the loss of initial compression of the flange joint and increasing the sealing force.

Seal Code	Seal Page	Description	Extreme conditions (Note 1)	Seating loads (Note 2)	Springback (Note 3)	Vacuum sealing (Note 4)	Pressure (MPa)	Max. working temp. (°C) Cryogenic to	Standard material Seal (Note 5)	Standard material Coating
Type MOT 	8	Pressurized	A	C	C	A	40 MPa	850°C		
Type MOV 	8	Vented internal	B	B	C	C	1000 MPa	600°C	Mild steel	PTFE
Type MOW 	8	Vented external							Stainless steel 316L 321	Silver
Type MOU 	9	Non-pressurized	C	B	C	C	4 MPa	400°C	Inconel® 600	Nickel
Type MOS 	9	Solid	C	D	D	B	4 MPa	500°C	Copper	
Type MCX 	11	Internal pressure	B	A	A	C	200 MPa	750°C	Inconel® 718	PTFE
Type MCY 	11	External pressure							Inconel® 750	Silver

Properties: A = Excellent, B = Good, C = Satisfactory, D = Poor.
Inconel® is a trade mark of INCO Alloys International, Inc.

Notes:
1) Extreme conditions could be radiation, searching gases, long life.
2) Thin wall material should be used to give low seating loads. This must be specified as seals are made in standard wall unless otherwise requested.
3) The elastic recovery of the seal is known as the 'Springback'. Springback depends upon wall thickness, and also heat treatment for Wills Rings® C. Higher seal resilience gives higher springback, and higher seating loads.
4) Ability to seal a hard vacuum to meet a leakage rate of $Q < 1 \times 10^{-9}$ mbar.l.s^{-1}.
5) Other material options are available. Not all materials are available in all sizes. Not all coating available for all materials. See temperature limitations (Table 2.6).
(Source: Trelleborg Sealing Solutions)

Figure 3.9: Application of different metal O-Ring types [12].

CHAPTER 4

RESULTS AND DISCUSSIONS

4.1 Free Body Diagram of Bolted Flange Connector

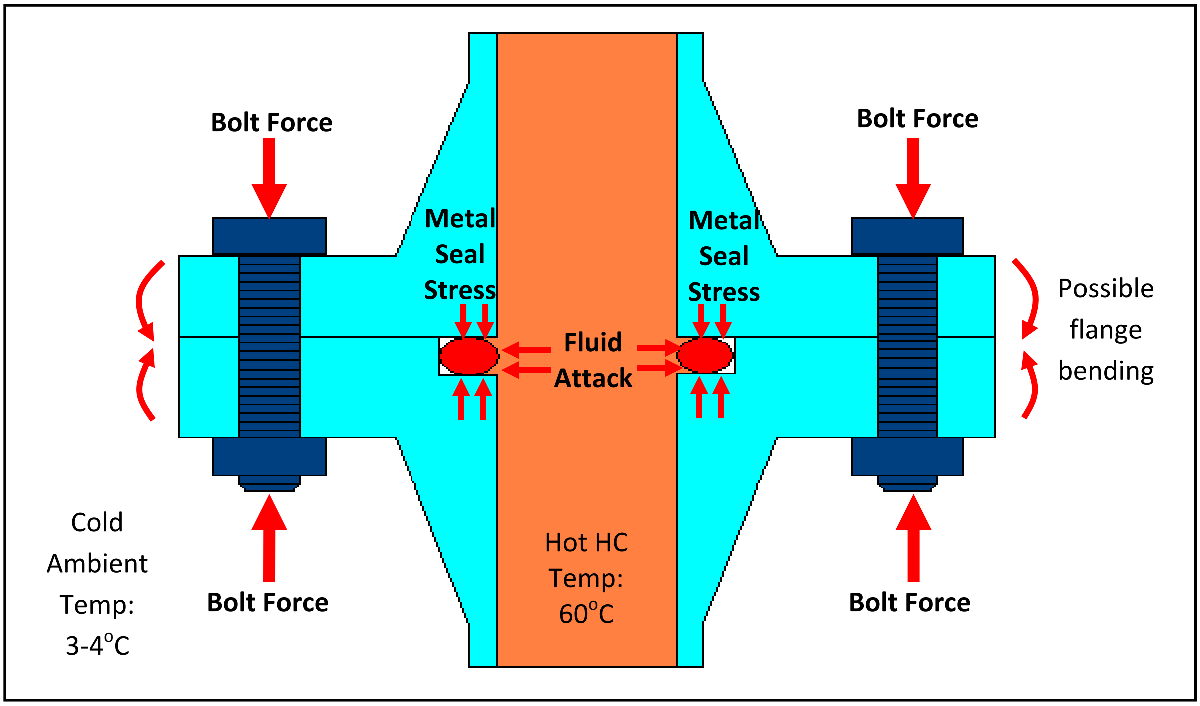


Figure 4.1: Free Body Diagram of Bolted Flange Connector.

4.2 Failure Analysis Diagram of Bolted Flange Connector Seal

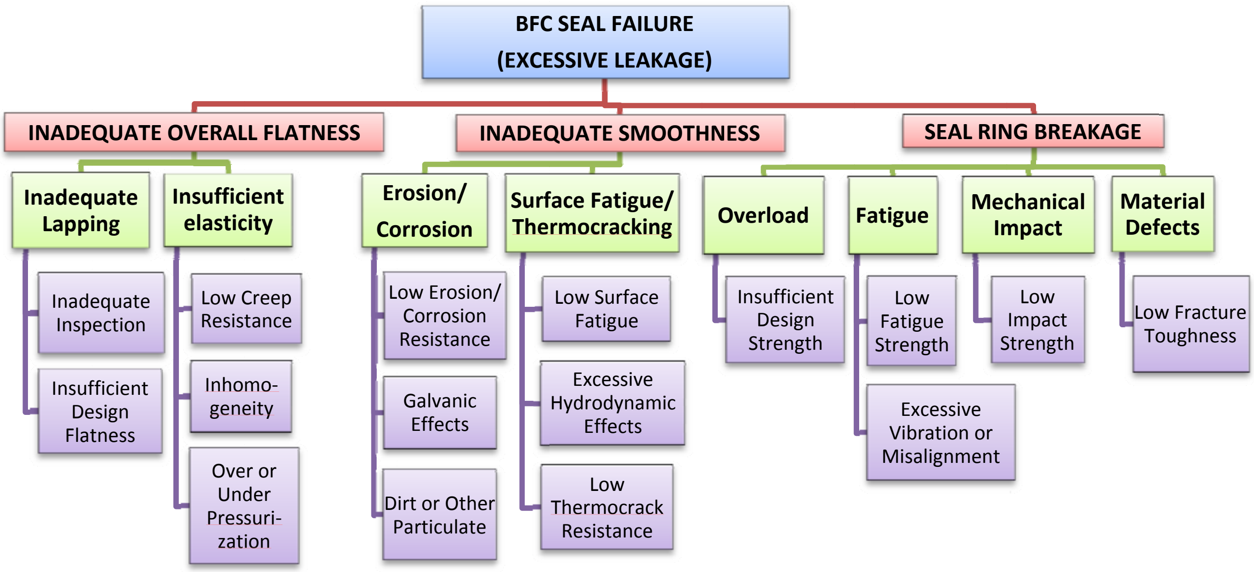


Figure 4.2: Failure Analysis Diagram of BFC Seal.

4.3 Material Selection for metal seal inside BFC

The flange dimension was taken from ANSI Forged Steel Flanges by Taylor Forge Canada Ltd. [29] while the dimension for seal was taken from Garlock Helicoflex catalog [28]. The nominal pipeline size of 10' and 1500lb welding neck flanges were used for this project. For 2000, 3000, and 5000 psi applications, API specified an increase in material yield strength to the respective ASA B16.5 flanges: 600, 900, and 1500 lb [30]. Since the gas pipeline design pressure for Kikeh field is 5200psig, a 1500lb flange has been chosen. The 1500lb welding neck flange dimension is shown in Table 4.1 below.

Table 4.1: 1500lb Welding Neck Flange Dimension [29].

Nominal Pipe Size	1500lb welding neck flange				Unit
	O	C	Y	No. and size of hole	
10	23	4.25	10	12 - 2	inches
254	584.2	107.95	254	12 – 50.8	mm

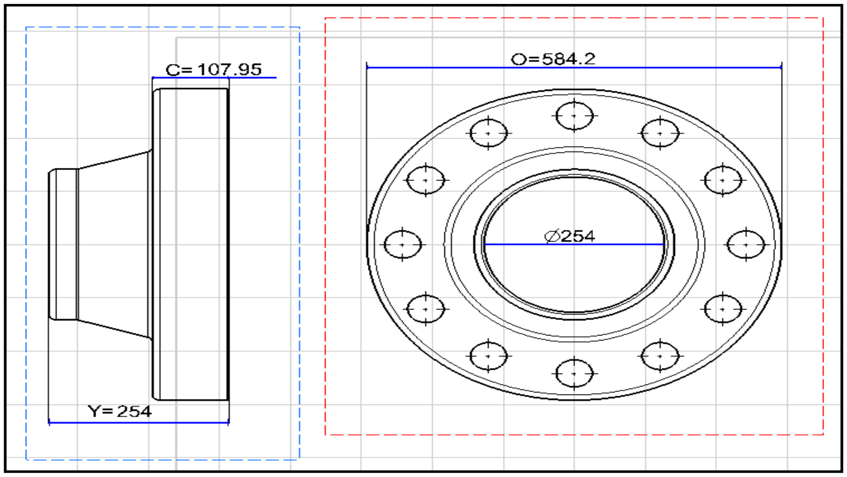


Figure 4.3: Top Flange Diagram.

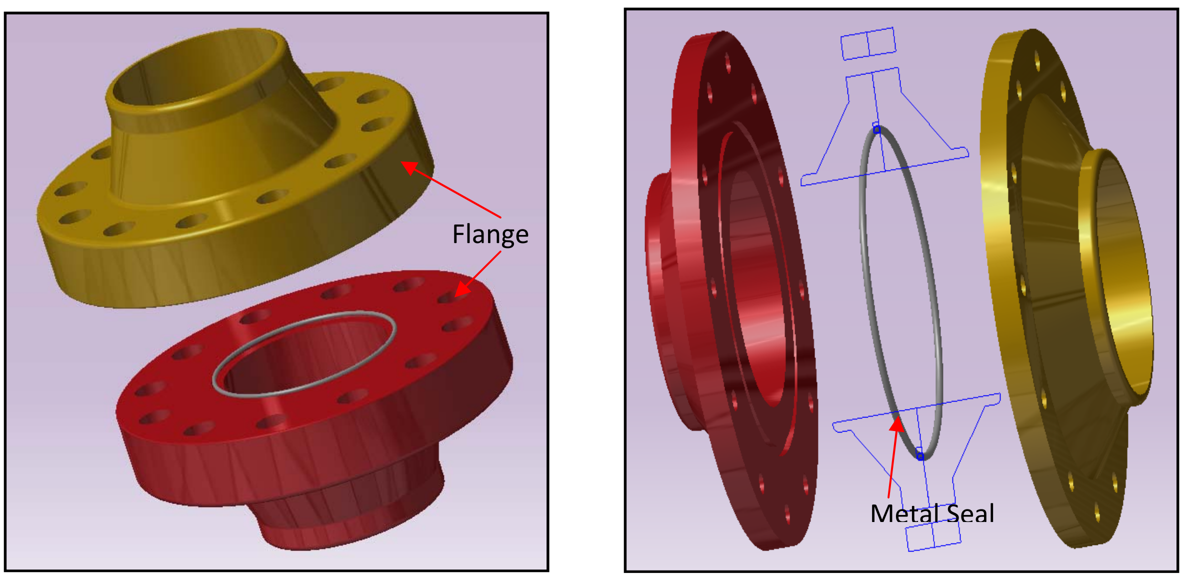


Figure 4.4: Metal O-Ring inside Bolted Flange Connector modeled by CATIA.

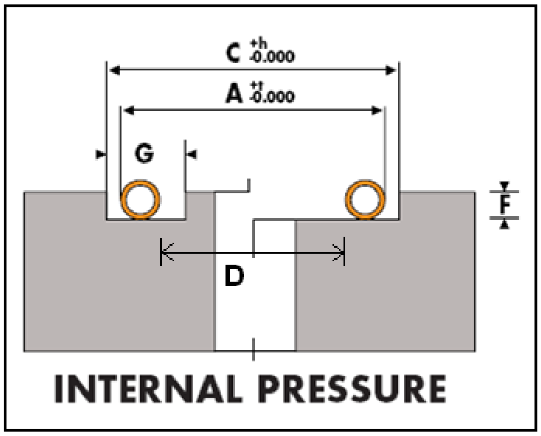


Figure 4.5: Typical Diagram of Seal Dimension.

Table 4.2: Seal Dimension [28].

SEAL						GROOVE DESIGN							
Nominal Tubing Diameter C.S. (in)	(mm)	Seal O.D./I.D. Range* (in)	(mm)	Seal Tolerance t (in)	(mm)	Clearance** CL (in)	(mm)	Groove Tolerance h (in)	(mm)	RECOMMENDED GROOVE DEPTH F (in)	(mm)	MINIMUM GROOVE WIDTH G (in)	(mm)
.035	0.9	0.250- 4.000	6.4- 102	.005	.13	.006	.15	.004	.10	.028/.030	0.71/0.76	.055	1.4
.063	1.6	0.500- 10.000	12.7- 254	.005	.13	.006	.15	.004	.10	.050/.052	1.27/1.32	.090	2.3
.094	2.4	1.000- 15.000	25.4- 381	.005	.13	.008	.20	.004	.10	.071/.075	1.80/1.91	.125	3.2
.125	3.2	2.000- 40.000	50.8-1270	.005	.13	.008	.20	.004	.10	.097/.101	2.46/2.57	.160	4.1
.156	4.0	3.000- 50.000	76.2-1270	.005	.13	.014	.36	.006	.15	.123/.127	3.12/3.23	.200	5.1
.188	4.8	4.000- 50.000	101.6-1270	.005	.13	.014	.36	.006	.15	.147/.151	3.73/3.84	.250	6.4
.250	6.4	5.000- 50.000	127.0-1270	.008	.20	.019	.48	.008	.20	.197/.201	5.00/5.11	.350	8.9

* Nominal Diameter(does not include plating thickness)
** Between Seal Diameter and Groove Diameter

Dimensions in inches | Dimensions in mm

Based on Nominal pipe size (gas flowline) = 10 inch = 254mm,

Assume Seal ID (D) = 11 inch = 279.4mm

By using Nominal tubing diameter = 6.4mm (last row from Table 4.2),

Clearance (CL) = 0.48mm

Recommended Groove Depth (F) = 5.11mm

Minimum Groove Width (G) = 8.9mm

Seal OD (A) = D + Nominal tubing diameter = 279.4 + 6.4 = 285.8mm

Assume maximum plating thickness = 0.002in = 0.0508mm,

Groove OD (C) = A + CL + 2(Maximum plating thickness)

= 285.8 + 0.48 + 2(0.0508)

= 286.3816mm

Table 4.3: Standard Tubing Dimension [28].

STANDARD TUBING							
Cross Section C.S.		WALL THICKNESS					
		Thin		Medium		Heavy	
in	mm	in	mm	in	mm	in	mm
0.032	0.9	0.006	0.15	0.010	0.25	N/A	N/A
0.063	1.6	0.010	0.25	0.012	0.30	0.014	0.36
0.094	2.4	0.010	0.25	0.012	0.30	0.018	0.46
0.125	3.2	0.010	0.25	0.020	0.51	0.025	0.64
0.156	4.0	—	—	0.020	0.51	0.025	0.64
0.188	4.8	—	—	0.020	0.51	0.032	0.81
0.250	6.4	0.025	0.64	0.032	0.81	0.049	1.24

From Table 4.3, for Tubing Cross Section = 6.4mm, the wall thickness, t = 1.24mm (Heavy)

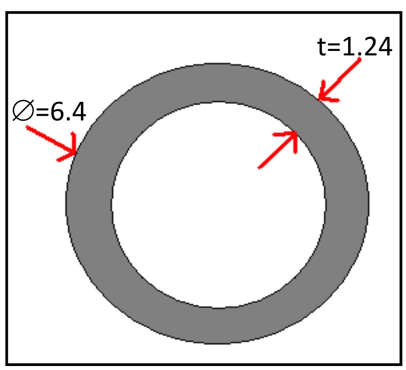


Figure 4.6: Standard Tubing Dimension Diagram

Table 4.4: Y2* and Km Values [28].

Y2* VALUES

Cross Section C.S.		Ideal Compression e2		Y2* Thin		Y2* Medium		Y2* Heavy	
in	mm	in	mm	lb/in	DaN/cm	lb/in	DaN/cm	lb/in	DaN/cm
0.035	0.9	0.006	0.15	457	80	1028	180	1485	260
0.063	1.6	0.012	0.30	571	100	799	140	1256	220
0.094	2.4	0.020	0.50	343	60	514	90	1313	230
0.125	3.2	0.026	0.65	343	60	1142	200	2056	360
0.156	4.0	0.031	0.80	—	—	857	150	1428	250
0.188	4.8	0.039	1.00	—	—	657	115	2113	370
0.250	6.4	0.051	1.30	799	140	1370	240	3026	530

Km VALUES

MATERIAL	Km
321 SS	1
Alloy 600	1.1
Alloy X750	1.3

Table 4.5: Kd values [28].

Kd VALUES

Diameter from:	0.0"	0	0.75"	19	1.2"	30	2"	50	3"	75	6"	150	10"	250	18"	450
Diameter to:	0.75"	19	1.2"	30	2.0"	50	3"	75	6"	150	10"	250	18"	450		
Kd Value	1.4		1.3		1.2		1.1		1.0		0.9		0.8		0.8	

Table 4.6: Diameter/ Cross Section Guidelines [28].

DIAMETER/C.S. GUIDELINES

Cross Section	0.035"	0.063"	0.094"	0.125"	0.156"	0.188"	0.250"
	0.9	1.6	2.4	3.2	4.0	4.8	6.4
Diameter from:	0.250"	0.500"	1"	2"	3"	4"	5"
	6	12.5	25	50	75	100	125
Diameter to:	4"	10"	20"	40"	50"	60"	80"
	100	250	500	1000	1250	1500	2000

Ideal compressive load, Y2 = Km x Kd x Y2* [28]

Y2* = linear load

Km = material factor

Kd = diameter factor

From Table 4.4, 4.5 and 4.6, Y2* for 6.4mm cross section under heavy application = 530 daN/cm and Kd value for diameter from 250mm to 450mm = 0.9 (Base on Seal OD (A) = 285.8mm).

Y2* = 530 daN/cm = 530 kN/m

Kd = 0.9

The gap between top and bottom flange before the compression occur is

= Nominal Tubing Diameter (CS) – F
= 6.4 – 5.11 = 1.29mm

The pressure, P = Y2/gap

For this project, the calculations were done on Stainless Steel 321, Alloy 600 and Alloy X750.

Table 4.7: Temperature limits of metal O-Ring materials [28].

TEMPERATURE	O-RING MATERIAL
Cryogenic to 700°F (371°C)	Stainless Steel 321
Cryogenic to 1000°F (538°C)	Alloy 600
Cryogenic to 1400°F (760°C)	Alloy X750
Above 1400°F (760°C)	Consult our engineering staff

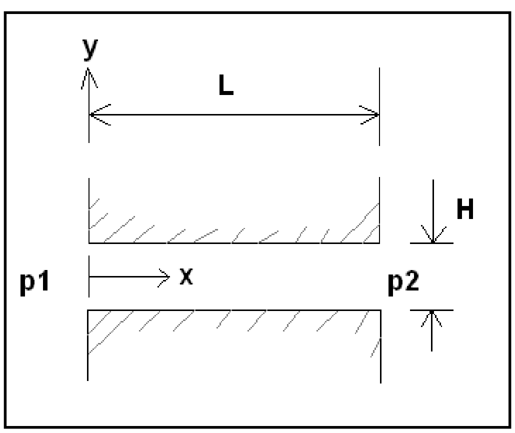
Table 4.8: Comparison of the compressive load between materials.

Material	Y2* (kN/m)	Kd	Km	Y2 (kN/m)	P (MPa)
Stainless steel AISI 321	530	0.9	1.0	477.0	369.77
Alloy 600	530	0.9	1.1	524.7	406.74
Alloy X750	530	0.9	1.3	620.1	480.70

From Table 4.8, Alloy X750 gives the highest compressive load 620.1kN/m compared to the rest. The internal pressure inside the gas pipeline is just 35.954MPa. All these materials satisfy the pressure requirement to compress the seal and prevent leakage. Stainless steel AISI 321 has been chosen for metal O–Ring inside Bolted Flange connector due to cost consideration.

4.4 Leakage Rate

The first assumption is that leakage occurs down passages which are of constant height, H, and whose width is large compared to height, so that effectively the gas is flowing two parallel flat surfaces. The passage is L (L>>H). x- and y- coordinate axes are defined as in Figure 4.4.



Legends:

H = height of passage through which gas leaks
L = length of passage through which gas leaks
p1 = internal pressure inside gas pipeline
p2 = external pressure outside gas pipeline

Figure 4.7: Gap between the top and bottom flange.

The leaking gas is assumed to be adequately modeled as a continuum, rather than as a set of discrete molecules, and is taken to be perfect gas, so that the pressure P, the density ρ and the temperature T are related by [31]

$$P = \rho RT$$

where R is gas constant. It will be assumed the temperature is constant and the flow is steady laminar.

For a compressible gas, this applies locally at any x, but ρ varies with p, so the mass leakage rate per unit width passage given by [31],

$$L_{RM} = \frac{H^3}{24RT\mu L}\left(p_1^2 - p_2^2\right) \ \ldots\ldots\ldots\ldots\ldots\ldots(1)$$

Leakage is from a gauge pressure p_i to the atmosphere at p_a, so $p_1 = p_i + p_a$ and $p_2 = p_a$. The pressure ratio P_R is defined as p_i/p_a. It is convenient to define a non-dimensional leakage rate L_{ND} as follows [31]

$$L_{ND} = \frac{L_{RM}}{\left(\frac{p_a^2 H^3}{24RT\mu L}\right)} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(2)$$

By substituting $p_1 = p_i + p_a$ and $p_2 = p_a$ into (2), the equation for L_{ND} will be simplified to

$$L_{ND} = P_R^2 + 2P_R$$

For this project, methane gas is used. Table 4.9 below shows the methane gas properties.

Table 4.9: Properties of methane gas [32-33].

Properties	Value
Molecular Formula	CH_4
Molar Mass	16.042 g/mol
Density, ρ	0.678 kg/m^3
Dynamic viscosity, μ	1.1×10^{-5} kg/ms
Methane gas constant, R	518 J/kgK

P_i = 5214.7psia = 35.954MPa

P_a = 13.338MPa

$T_i = 60^oC + 273 = 333K$

L = 89.3mm = 0.0893m

H = 1.29mm $=1.29 \times 10^{-3}$m

By substituting all the data into the equation, we will get

P_1 = 35.954 + 13.338 = 49.292MPa

P_2 = 13.338MPa

P_R = 35.954/13.338 = 2.69561

L_{RM} = 0.0189796 Pam^3/s

L_{ND} = 12.6575

CHAPTER 5
CONCLUSION & RECOMMENDATION

5.1 Conclusion

As for the conclusion, there are three main factors contribute to the leakage cause in the Subsea Production System Bolted Flange Connector Seal which are inadequate overall flatness, inadequate smoothness and seal ring breakage. Inadequate overall flatness is due to inadequate lapping between flanges and insufficient elasticity of the seal. Inadequate smoothness is caused by the erosion/ corrosion and surface fatigue/ thermocracking. Overload, fatigue, mechanical impact and material defect contribute to the seal ring breakage. Overload commonly occur because of insufficient design strength of the seal itself. Low fatigue strength in the seal and excessive vibration or misalignment can increase the fatigue problem. Low impact strength can increase the mechanical impact on seal thus lead to seal ring breakage. Besides, material defect inside seal occur because of low seal fracture toughness.

Metal O-Ring is the most feasible metal seal for High Pressure SPS Bolted Flange connector due to its good properties and characteristics that can adapt to the harsh deepwater environment. The specification for metal O-Ring are it is the pressurized type and can withstand the pressure up to 40MPa with wide range of working temperature (from cryogenic to 850^{o}C). O-Ring outer diameter (OD) is 285.8mm and inner diameter (ID) is 279.4mm. O-Ring tubing cross section is 6.4mm and the tubing wall thickness is 1.24mm. The material used for metal O-Ring is stainless steel AISI 321 with compressive load equal to 477kN/m.

5.2 Recommendation

The purpose of a metal seal is to prevent leakage, but all seals leak to some controlled degree depend on their application i.e. for heavy sealing application, leakage rate, Q $<10^{-9}$ Torr.Liters.s-1 [28]. However, it is important to note that this minimal leakage can be so restricted that specific designs are capable of adequately meeting all emission requirements. Seal failure is defined as excessive leakage. Further investigation need to be done in the leakage rate calculation. The relationship between leakage rate and compressive load need to be found in order to have an accurate leakage rate formula for specific material. Besides, this project considers the leakage during operation only not during the plant shut in. Analysis should be made on both conditions to have an optimum result.

There are a lot of metal seal ring types other than O-ring been used in industry application such C-ring, V-rings and U-rings. The comparison can be made between all these rings to find which one will have a better performance in preventing the leakage rate in high pressure subsea condition.

In addition, by using more than one seal, such as three layer metal seal can enhance the sealing performance. Coating for metal seal also can prevent the seal from any unnecessary damage on the seal surface. Besides, coating also can slow down the erosion and corrosion attack on the seal surface. These improvement methods need to be studied and require an extensive research to find the most feasible one without ignoring the cost consideration.

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