Front End Engineering Design for Offshore Facility Equipment

by

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16976

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CERTIFICATION OF APPROVAL

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A project dissertation submitted to the

Mechanical Engineering Program

Universiti Teknologi PETRONAS

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(MECHANICAL)

Approved by,

____

(Assoc.Prof.Dr Fakhruldin bin Mohd Hashim)

Universiti Teknologi PETRONAS

TRONOH, PERAK

May 2015

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 reference and acknowledgements, and the original work contain herein have not been undertaken or done by unspecified sources or persons.

(MOHD FAIZ BIN RODZI)

ABSTRACT

Front End Engineering Design (FEED) is an important phase in engineering design. The purpose of doing FEED is to prevent major changes during the execution phase. However, it is an enormous challenge for the engineers to produce a good FEED. The experienced engineers are needed in making the lump sum estimation. The underestimate estimation may lead to major changes thus incur more cost. The objective of this project is to demonstrate the Front End Engineering Design (FEED) work in proposing design solution for water injection system. The FEED methodology of this project is based on the Emerson FEED capabilities that consist of FEED planning, data gathering and design basis. The Bokor Field re-development project is used as the case study for this final year project. The FEED work on the water injection system is scoped to the filtration system and deaeration system. The technical drawing of the filtration skid and the deaerating tower are established as the deliverables of the project. As the recommendation to improve this project, the project should include the whole subsystem and utilizing the related software. For instance, ROSA Version 6.1 and TorayDS Version 1.1.44. can be used to design the filtration system to get the accurate number of modules required to filter the water which eventually can estimate the size of the skid to accommodate the vessels of the filter.

ACKNOWLEDGEMENT

First and foremost, I would like to express my biggest gratitude to Allah the Al-Mighty for giving me the opportunity to do this research. Secondly, I would like to convey my gratitude to my supervisor, Dr. Fakhruldin bin Mohd Hashim, whom have offered me his relentless support and shared his knowledge in the process of completing this dissertation. On top of that, he explained to me all the basic and fundamentals of Front End Engineering Design.

I would also like to take this opportunity to dedicate a very special appreciation to my family especially my parents for their continuous encouragement and being so understanding during the process of completing this research. Finally, I would like to express my gratitude to my fellow friends for their help in doing the research.

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CHAPTER 1: INTRODUCTION

1.1: Project Background

Front-End Engineering Design (FEED) is a process of developing design concept in order to establish the technical requirement and design guidelines including scope, schedule and cost [1]. It is usually carried out after the feasibility conceptual design as one of the in-depth engineering practice to properly design a project. The purpose is to refine the conceptual solutions generated in the earlier stage including the cost estimation until +/- 10% closer to the design that would be approved for construction later [2]. The FEED documents that consist of total costs, weight and layout of the plants will be the foundation for the companies to bid the Execution Phase Contracts (EPC).

Due to the demand of oil and gas that getting higher, FEED becomes more critical in determining the feasibility of the specific areas especially when the installation area of offshore production plant is getting into deep sea. There are many facilities in the offshore production plant that require a lot of equipment installation. One of the facilities that is going to be focused on this project is water injection facility. There is some mechanical equipment in the water injection facility that needs to be properly design in order for the facility to deliver the required function. All these require thorough FEED studies as insufficient FEED studies can lead to project delays and cost overruns [3]. Thus, engineers need to fully understand the FEED process and its approach so that a good FEED can be properly done.

1.2: Problem statement

A proper FEED studies that is aimed by all companies should reflect the project specific requirement as provided by the client. In addition, the estimation that includes the detailed functional scope of the design has to be as accurate as possible since one of the objectives of doing FEED is to prevent major changes during the execution phase.

However to produce a good FEED is an enormous challenge for the engineers in order to make billion dollar engineering and construction projects successfully delivered. One of the challenges is to perform a proper FEED studies. The underestimate estimation on quantities, equipment, material and other requirement for the project will cause some problems while executing the project. Numerous changes that need to be done will be encountered thus lead to the delays in completing the project and increase the cost. Besides that, inadequate design basis also will affect the FEED studies [3]. It may cause the change of design which will also cause project delay and may incur cost.

Sometimes the problem of having highly-skilled and experienced engineers in multiple disciplines is part of the challenge in establishing a good FEED. Their experiences are needed in making the lump sum estimation for bidding process [3].

1.3: Objectives

The objective of this project is to demonstrate the Front End Engineering Design (FEED) work in proposing design solutions for a water injection system. Thus, to fulfil the objective, the following activities need to be done and presented as the result of this project.

- Identify a FEED model that would be used to demonstrate the FEED work
- Establish a design concept that would be the main reference for FEED work
- Establish the technical drawings

1.4: Scope of study

FEED covers a broad scope including schedule and cost. In addition, among the FEED deliverables are process description, design basis description, equipment process datasheet and many more. In this project, the scope that will be covered only the performance of the major equipment and their physical description.

Besides that, the water injection system which is commonly used on the offshore platform to maintain the reservoir pressure so that the production capacity is met would be the main focus of this project. To be specific, the performance of the water treatment system and the physical description of filters and deaerating tower to deliver the system performance would be presented as the deliverables of this project.

CHAPTER 2: LITERATURE REVIEW

2.1: Front End Engineering Design

2.1.1 Overview

FEED is an early stage of design work done after the feasibility conceptual design stage. It is the process of conceptual development base on the requirements from the client's specification [1]. The determined specification will be roughly estimated usually up to the +/- 10% at the FEED stage before it will be thoroughly examined and refined at detail engineering stage [2]. A proper FEED work will help to avoid the major changes during the execution phase that will lead to the consequence of incurring extra cost.

The reason of implementing FEED is to utilize the time where the possibility to make changes to the design is still acceptable and the cost to make those changes is still low. There would be the upfront costs and time consumed at the FEED stage but it is relatively minimal as compare to cost of changes at later stages of project [3]. In addition, through FEED work the possible risks can be identified and could define the solutions for the project.

FEED outputs estimate the overall cost, weights and layout of the designed system [4]. The first FEED activity to obtain the FEED results is determining the design criteria of the systems such as the engineering consideration of equipment, utilities and piping of the system. After that, the overall process flow and the requirement that the system must deliver is determined in order to calculate the physical parameter, the thermodynamic properties and utilities specifications for each equipment in delivering the overall system requirement. Thereafter, the related drawings such as process flow diagram (PFD) and piping and instrument diagram (P&ID) can be prepared based on the previous activity. The aim of performing the mentioned processes is to obtain the estimation on the system layout, cost and weight as per FEED output [4].

2.1.2 FEED Model

Figure 1 shows the FEED model introduced by Schmidt [5] in his text book which divided the process into three parts begin with the establishment of the system architecture, configuration design and parametric design which eventually each part sets clear boundary on the engineering works that need to be done.

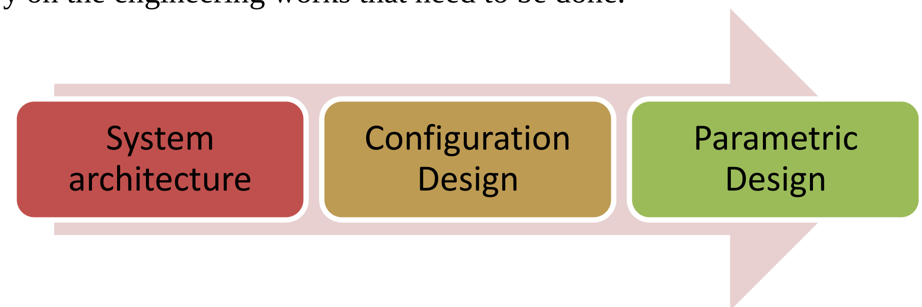


Figure 1: FEED model **[5]**

System architecture is basically a process of determining the function that the system must perform and arrangement of the equipment needed to carry out the function of the system. Basically it is about getting a big picture of the system by creating the schematic diagram and rough geometric layout that allow the designer to identify the interactions between equipment.

The design process is preceded with configuration design stage where shape and general dimension of the components are established. Besides that, the function of all equipment is clarified and presented separately in an appropriate inflow and outflow diagram. The simplicity and safety of the design also emphasized at this stage. The detailing process on what have been done during the configuration design stage is done in parametric design stage. The exact values, dimensions and tolerances are determined during this stage.

Figure 2: Emerson FEED model **[2]**

On the other hand, Emerson FEED model comprise of five stages as shown in Figure 2. The FEED work starts with FEED planning where all the engineering considerations related to the system are listed out. Then the data gathering process is done according to the scope that has been planned. In design basis, the process of generating the solutions is done by performing the calculations based on the gathered data in order to ensure the design met the expectation. The output will be analyzed and estimated by the engineers based on experiences and engineering standards. Final design will be documented at the end of the FEED work.

Cimation is another engineering service company that provides the FEED service in oil and gas industry. It has its own model in doing FEED work that has seven stages. The process begins with defining the system until the implementation plan as the final deliverable, the activities involved throughout the FEED work are similar to the Emerson FEED work.

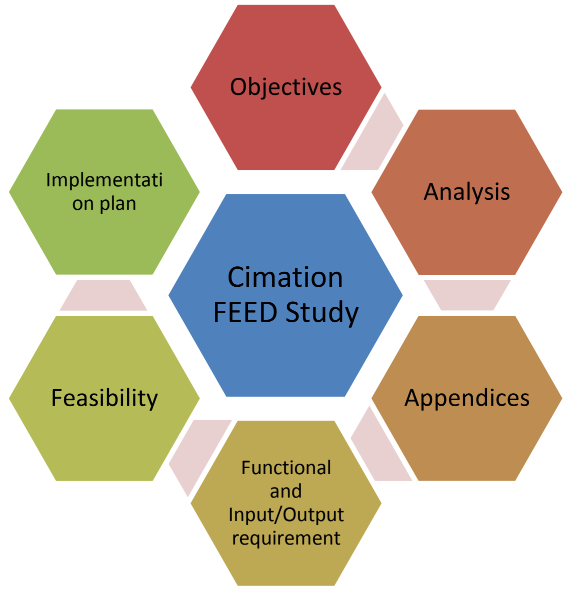


Figure 3: Cimation FEED model **[1]**

2.2: Water Injection System

2.2.1 Overview

The water injection technology is one of the offshore facilities that play a crucial role in improving the oil recovery by increasing the reservoir pressure. Taking example of Delta South Field case, the implementation of water injection resulted in increasing percent oil recovery for about 10% while for Bonga case, the presence of water injection might boost the oil recovery from 125 million barrels to approximately 650 million barrels [6]. However, the success of water injection is economically crucial as it must be fully operational and reliable, thus there are considerations that should be taken in design and operation of water injection system.

A successful water injection system requires a water conditioning system that can provide a good filtration to the solid content in the injection water that might cause serious well plugging problem. The standard water conditioning facilities have been design to handle the water capacity of 1000, 4500 and 10 000 barrels of water per day and all components involved are unitized on skids to form compact facilities that is favorable for offshore application [6]. Sea water lift pump, filter, deaerating tower, accumulator tank and the injection pump are among the components that form a water injection system as in the typical schematic flow diagram shown in the Figure 4.

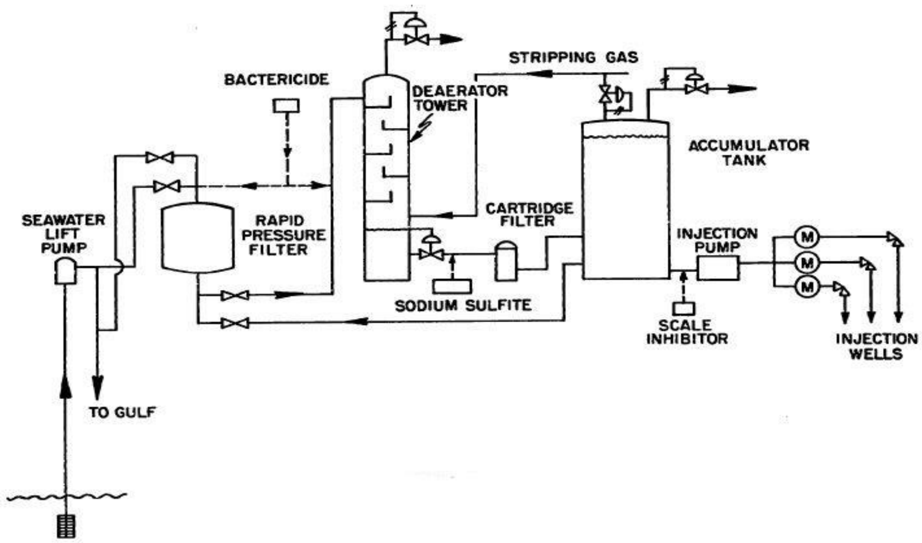


Figure 4: Schematic flow diagram of typical water injection system **[6]**

2.2.2 Engineering Consideration

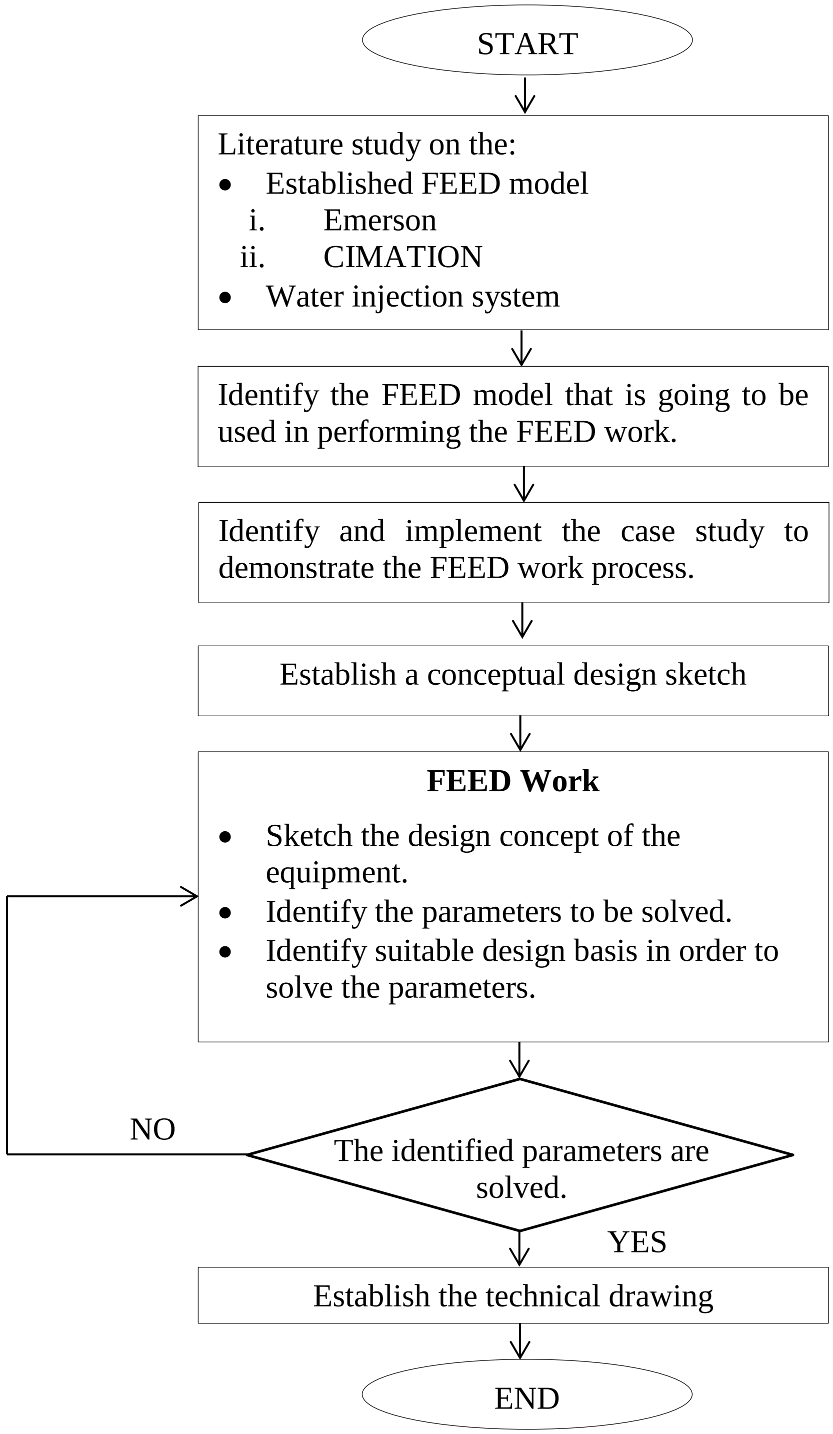
A successful water injection system requires a water treatment system that can provide injection water with the amount of suspended solids that will not cause the serious plugging problems and harmful plugging deposition [7]. Besides that, the injection water may contain the appreciable amount of oxygen that could be highly corrosive. Thus the water injection system must provide a method to remove the oxygen to the acceptable level.

On the other hand, as the application of the water injection system is on the offshore platform, the engineers must take into consideration about the limited space available on the platform. The system should be mechanically simple and dependable so that it will operate with limited attendance. Besides that, the design should be compact as to conserve the limited space available. The application of the system must consider of not consuming substance that could present the hazards on the platform.

CHAPTER 3: METHODOLOGY

3.1: Overall Project Flowchart

Following is the overall project flowchart that summarizes the activities for this project.



The main objective of this project is to demonstrate the Front End Engineering Design (FEED) work in proposing design solution for water injection system. Thorough studies on literature, related engineering handbooks and technical papers that cover about the established FEED model and water injection system have been done beforehand in order to have a clear understanding about the project then only the project methodology can be developed to achieve the project objective.

Background study on the established FEED model

Two FEED models have been analyzed while doing the literature analysis which is Emerson and Cimation. Both models might have differences in the way of performing FEED but the outcome will satisfy the same objective which is to establish and define technical requirements of the system designed. Thus whichever models implemented will still lead to the objective of this project. The FEED model that is going to be adopted in this project is the Emerson FEED model.

Conceptual design sketch

FEED is the process of the conceptual development that comes after the conceptual design and feasibility study. Thus this project require a concept sketch of water injection system so that it can be further develop throughout the FEED process to establish the technical requirement of the system. The concept might be referred to the established technical paper that review the feasibility of the seawater injection system or the case study that is selected as the datum for the project.

Identify the case study

A case study is required for this project as it is going to be implemented in doing FEED work. The production data and the design concept are derived based on the case study. The Bokor Field re-development project is one of the potentials case studies to be implemented for this project.

FEED framework

Figure 5 shows the FEED process that is going to be adopted for this project. The water injection design concept will be further developed using this FEED model with the aim to establish the technical requirement of the system.

Figure 5: FEED framework for water injection system

i. FEED Planning

The FEED work begins with FEED planning phase where the important parameters that need to be solved are established in order to meet the FEED target output. The established parameters should be able to contribute in determining the plant layout, the total cost and the weight. As per scope for this project, the established parameters will address the physical attributes and performance of the major mechanical equipment in water injection system.

ii. Data Gathering

In solving the parameter, the production data has to be provided to the designer. In real industry practice, the target criteria are determined from the client's document. The good quality of treated seawater and sufficient injection pressure of water to the wellhead are the major concern in designing the water injection facility.

iii. Design basis

In designing process, design basis need to be established that will be the guidance in solving the parameters required. In this project, a design procedure in designing the facility equipment for the water injection system will be establish including the required information to solve the required parameters. The filtration handbooks and Pressure Vessel Design Manual that based on ASME Sec. VIII Div. 1 standard are among the basis of design for this project.

Establish the technical drawing

The technical drawing of the equipment that has been focused on would be the project deliverables for this project. The drawings would be drawn based on the calculated parameters that have been solved based on the identified design basis.

3.2: Project Gantt Chart and Key Milestone

Table 1: Project Gantt Chart

Week/ Agenda	FYP 1							FYP 2						
	1-2	3-4	5-6	7-8	9-10	11-12	13-14	1-2	3-4	5-6	7-8	9-10	11-12	13-14
Literature study on the: • Established FEED model i. Emerson ii. Cimation • Water injection system		•												
Identify the FEED model that is going to be used in performing the FEED work. • Justify the scope of the FEED work										•				
Establish a conceptual design sketch of water injection system.														
FEED Work for the particular subsystem • Sketch the design concept of the equipment. • Identify the parameters to be solved. • Identify suitable design basis in order to solve the parameters.														
Establish the technical drawings the project deliverables.														•

CHAPTER 4: RESULT AND DISCUSSION

According to the scope of study in Chapter 1, water injection system will be the offshore facility that is going to be studied in this project. The aim of this project is to establish the plausible design solutions for offshore facility equipment. A case study would be implemented to the FEED framework that has been generated in order to satisfy the aim of this project.

4.1: FEED model

The FEED framework developed in this project is generated based on the Emerson FEED capabilities. The generated FEED model to satisfy the scope of this project is shown in Figure 6.

Figure 6: FEED model for water injection facility

i. FEED Planning

The parameters that are going to be solved are:

- Deaerating tower
  a. Tower diameter
  b. Height of the shell
  c. Height of the cone
  d. Thickness of head, shell and cone
- Filtration system
  a. Dimension of the filtration skid

ii. Data gathering

The data that is required to solve the parameters are:

- Design working pressure
- Design working temperature
- Design capacity

iii. Design basis

There are two main sources that have been used as the design basis for this project. First is the Pressure Vessel Design Manual that provides the formula in calculating the dimension and thickness of the deaerating tower. Besides that, a handbook established by the Lewabrane that provides the guideline to design the filtration system has been the design basis in designing the filtration system.

4.2: Case Study: Bokor Field Re-development Project

Bokor field is located in South China Sea, about 45km North West of Lutong, Miri, Sarawak, Malaysia. The water injection system for this case study consists of the following equipment:

- Water injection coarse filter
- Water injection fine filter
- Water injection deaeration tower
- Water injection booster pump
- Water injection pump

The Water Injection System is designed to provide water injection pressure of 145 barg (2100 psig) at water injection wellheads. The source of water for injection is deoxygenated seawater and will be pumped by Seawater Lift Pumps. The raw seawater from Seawater Lift Pumps will flow through the Water Injection Coarse Filters where particles of 80 microns and larger are removed. The seawater is further filtered in the Water Injection Fine Filters to remove particles of 2 microns and larger.

The filtered seawater is routed to the Water Injection Deaeration Tower for removal of dissolved oxygen to less than 20 ppbV without oxygen scavenger dosing. Furthermore, oxygen content in the seawater is reduced to less than 5 ppbV with oxygen scavenger dosing. The deoxygenated water is pumped by Water Injection Booster Pumps and Water Injection Pumps to the required water injection pressure of maximum 145 barg (2100 psig) at water injection wellheads.

4.3: Conceptual Design Sketch

The conceptual design sketch is required in this project before it can be proceed with the FEED work. The concept later will be further developed through FEED work. The sketch is drawn based on the water injection facility concept applied to the Bokor Redevelopment case study as shown in Figure 8. The concept was developed to deliver the function of water injection facility that must comprise of all required equipment.

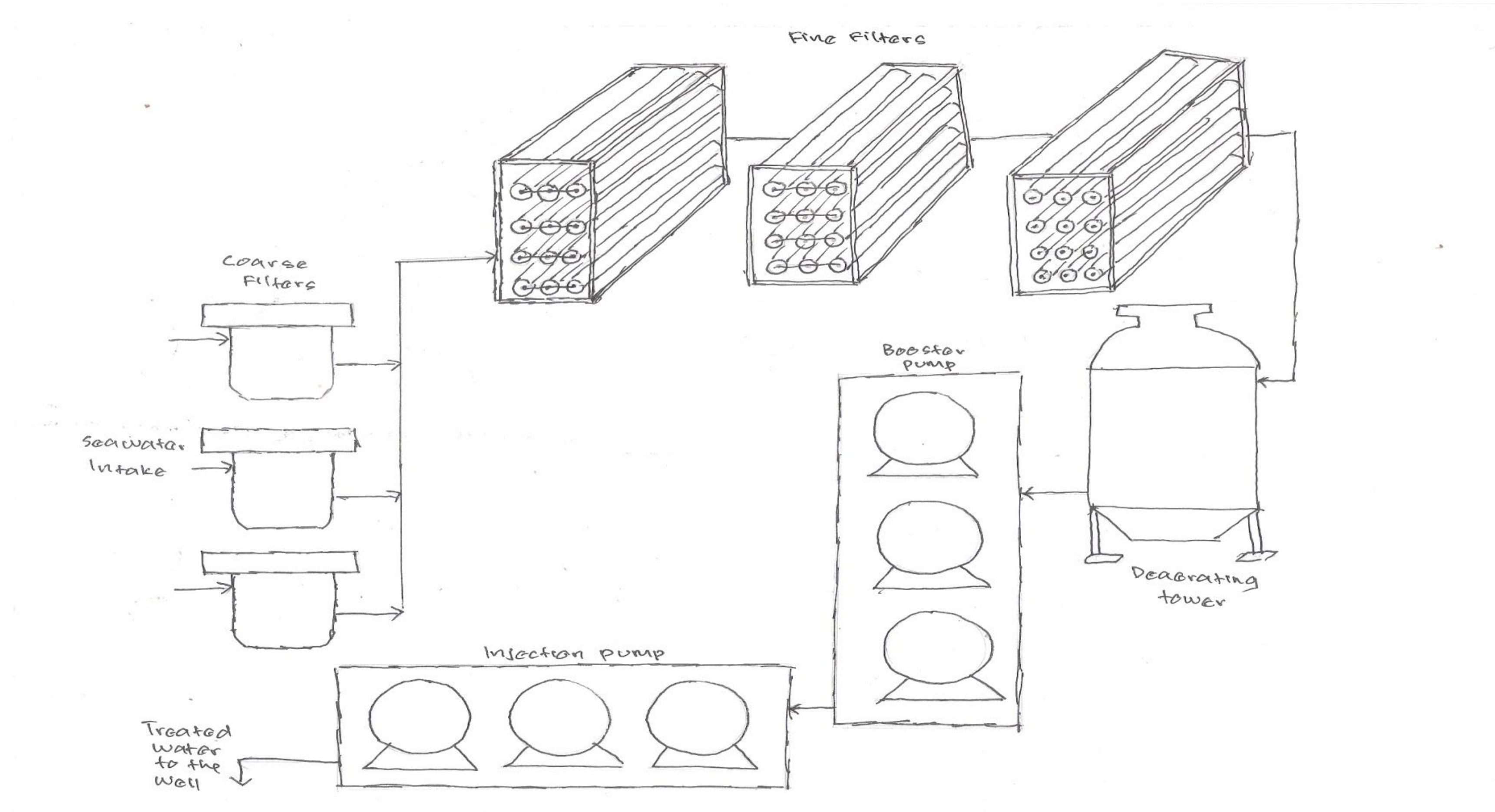


Figure 7: Conceptual design sketch of water injection system **[8]**

4.4: FEED Work

For this project, the FEED work will only focus on the deaeration system and filtration system.

4.4.1: Deaeration system

Based on the water injection system concept sketch in Figure 7, the deaerating tower should be vertical cylindrical type which has been sketch as illustrated in Figure 8. The deaerating tower could be divided into three parts which are head, shell and cone. The parameters that could be solved are:

i. Tower diameter
ii. Height of the shell
iii. Height of the cone
iv. Thickness of head, shell and cone

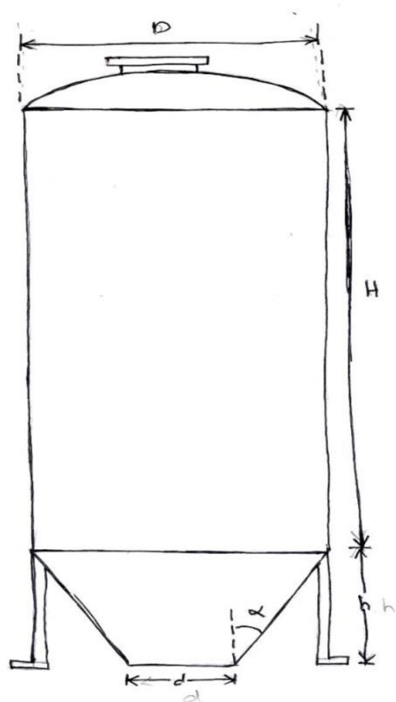


Figure 8: The concept sketch of deaerating tower

Assumption:

- H/D ratio = 3
- Required welding efficiency, E = 1
- Cone diameter, d = 8 in.
- $\alpha = 30°$

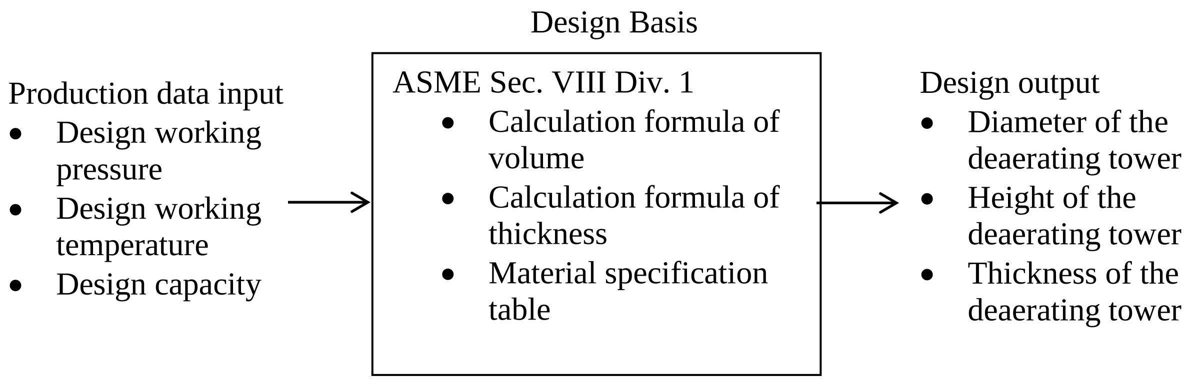


Figure 9: The block diagram of deaerating Tower design process

The dimension of the deaerating tower is estimated by assuming the Height/Diameter ratio is 3 and d = 8 inch (0.203 m) as per standard value recommended in ASME Sec. VIII Div. 1.

For the estimation purpose, the **design volume** can be calculated by using the given formula provided in the standard. The formula of pressure vessel volume is:

$\forall = \frac{\pi DH}{4} + 0.262\, h\, (D_i^2 + D_d^2 + d^2)$………. 1

Where d = 8 inch/0.203 m

h = 0.2881 $(D_i - d)\ for\ \propto = 30^{\circ}$……….. 2

By plug in H/D = 3 into equation 1,

$\forall = \frac{3\pi D_i^3}{4} + (0.262\ (0.2881(D_i - 0.196))\ \times ((D_i + 0.196D_i +\ 0.196^2)$

$\forall$ = 50 m^3

$50 = \frac{3\pi D_i^3}{4} + (0.262\ (0.2881(D_i - 0.196))\ \times ((D_i + 0.196D_i +\ 0.196^2)$ ……….. 3

In order to meet the volume requirement of 50 m^3, some possible values of D_i are tried and the the most appropriate D_i to be used indesiging the deaerating tower is 14 m.

Thus, insert D_i= 2.75 m into equation 3,

$$\frac{3\pi(2.75)^3}{4} + (0.262\ (0.2881(2.75 - 0.196))\ \times ((2.75 + 0.196(2.75) +\ 0.196^2)$$

=49.64≈50 m^3

Therefore;

D_i= 2.75m (108.27 in)

H = 2.75 × 3 = 8.25 m

h = 0.2888 (2.75 – 0.196) = 0.738 m

The thickness of the head, shell and cone also can be estimated based on the design working pressure and working temperature. The formulae to calculate the thickness for different head, shell and cone are listed in the table provided in Appendix 1. The formulae that are going to be used for this design in estimating the thickness are:

Thickness of head:

$$t_h = \frac{PD_i}{2SE + 0.2P}$$

Thickness of shell:

$$t_s = \frac{PR_i}{2SE + 0.4P}$$

Thickness of cone:

$$t_c = \frac{PD_i}{4\cos\ \alpha\ (SE + 0.4P)}$$

The production data provided on design working pressure and temperature are 957 psi and 650°F respectively. By referring to the Table 2, as the design working pressure is below 700°F, there are few materials that are possible to be used to design the deaerating tower. For this project, it is assumed that the deaerating tower will be constructed using SA-516 Gr. 70 as this is one of the popular steel grade in the market.

Table 2: Allowable stress for materials. **[12]**

Material Specification	Temperature Use Limit (°F)	Allowable Stress (psi)
SA-515 Gr. 60	700	14 400
	800	10 800
	900	6 500
SA-516 Gr. 70	700	16 600
	800	14 500
	900	12 000
SA-53 Gr. A	700	11 700
	800	9 300
	900	6 500
SA-106 Gr. B	700	14 400
	800	10 800
	900	6 500
SA-181 Gr. I	700	16 600
	800	12 000
	900	6 500

Material: SA-515 Gr. 70

The allowable stress, S = 16 600 psi

Therefore,

Thickness of head:

$$t_h = \frac{(957) \times (\ 108.27)}{2(16\ 600)(1) + 0.2(957)} = 3.10\ in.$$

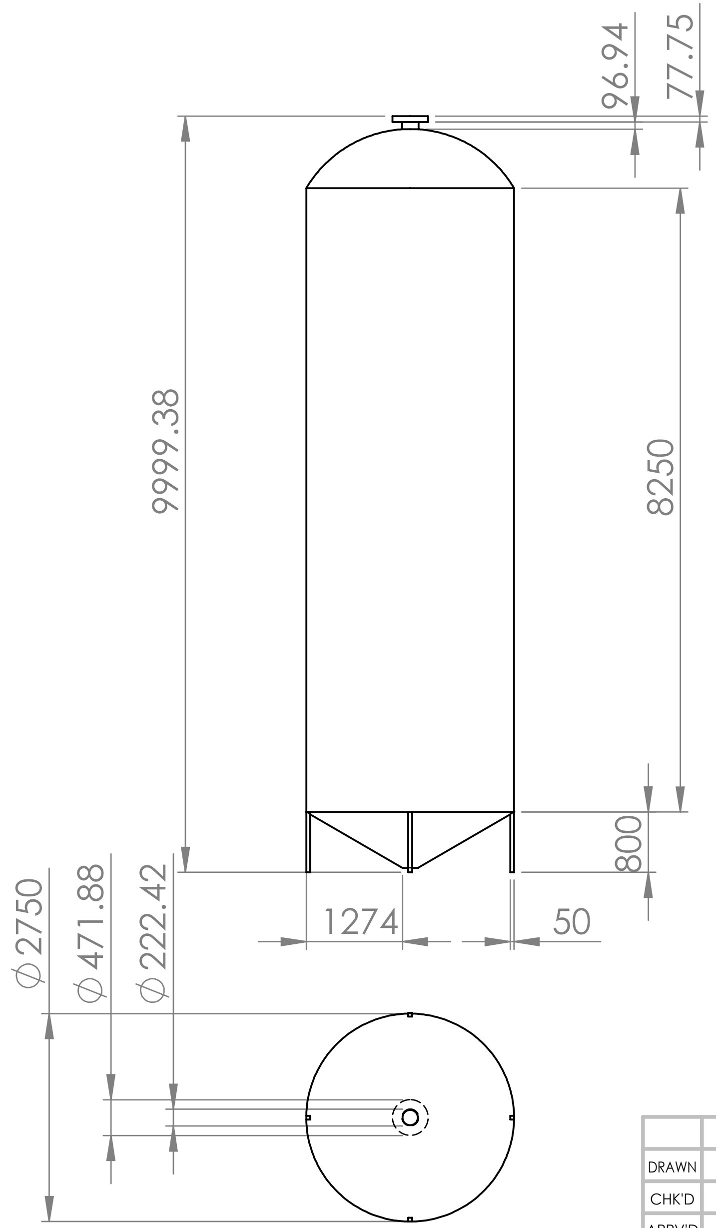
Thickness of shell:

$$t_s = \frac{(957) \times (54.135)}{2(16\ 600)(1) + 0.4(957)} = 1.54\ in.$$

Thickness of cone:

$$t_c = \frac{(957) \times (108.27)}{4 \cos 30\,(16\,600 + (0.4 \times 957))} = 1.76\ in.$$

The technical drawing of the filtration skid is established and presented in the page 23.



	NAME	STUDENT ID	DATE
DRAWN	Faiz Rodzi	16976	3/9/2015
CHK'D			
APPV'D			
MFG			
Q.A			

TITLE:

Tower

MATERIAL:

DWG NO. 2

A4

WEIGHT:

SCALE:1:200

SHEET 1 OF 1

4.4.2: Filtration system

The filtration system is the first subsystem that the water will past through before being injected into the well. The filters will be installed horizontally in a skid like the concept sketch that has been illustrated in Figure 10. The parameters that will be solved are the dimension of the filtration skid.

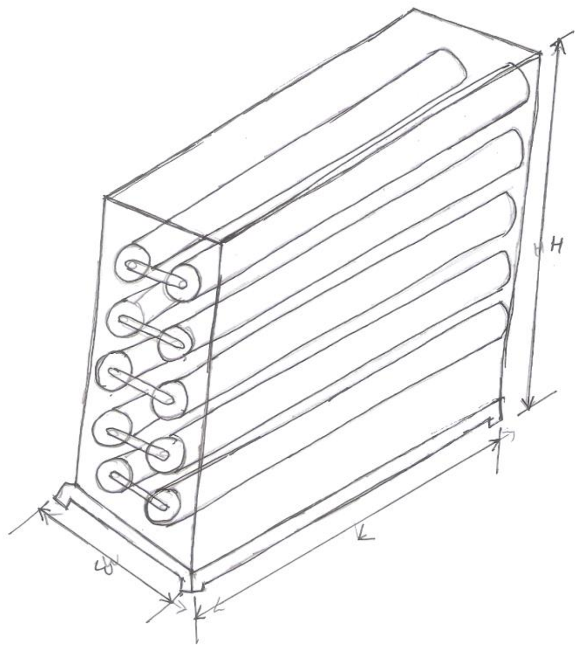


Figure 10: The concept sketch of filtration skid.

The first information that should be the basis in designing the filtration system is the requirement on the size of particle that need to be removed. It will determine the type of filter that suitable for the system as guided in the Table 3.

Table 3: The pore size of fine filter **[9]**

Type of filter	**Pore size (μm)**
Micro-filter	0.1 – 0.2
Ultra-filter	0.01 – 0.05
Membrane Cartridge Filter	1.0
RO filter	TDS (1 psi for every 100mg/L)

* TDS – Total Dissolved Solid

In identifying the filtration skid dimension, the most important parameter that needs to be solved in designing the filtration system is the number of module required to meet the desired productivity. It can be calculated by using the following equation:

$$N = \frac{Q_p}{J_w} \times MA$$

N = Number of modules

Q_p = Product flowrate, gallon per day

J_w = Water flux, gfd

MA = Membrane area per module

The desired water flux should be selected as per recommended based on the feed water source. The recommended value of water flux is shown in the Table 4.

Table 4: The recommended water flux value **[9]**

Feed water type	Municipal supply	Brackish well	Surface water	Seawater intake	RO permeate	Seawater Beach Well
Water flux (gfd)	22 (19 – 25)	29 (25 – 33)	27 (23 – 29)	17 (15 – 19)	35 (30 – 39)	17 (15 – 19)

There are various membranes areas available in the market with standard 8-inch diameter of the module. The most common model of filter available in the market is manufactured with 365 ft^2 and 400 ft^2 membranes area. The product flowrate is depending on the requirement from the client specification.

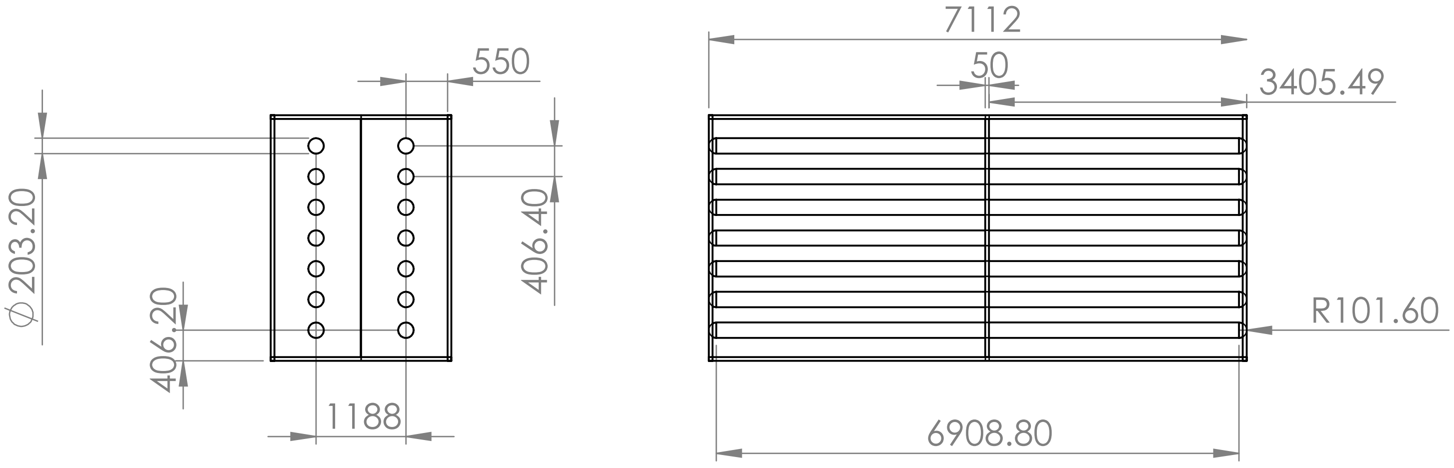
By calculating the number of module required, the number of pressure vessels that will be fit on the water injection skid can be estimated including the dimension of the skid. However, the design process get very tedious considering many variables that must be addressed by the design such as number of stages and number of arrays. Usually the designers will utilize the design software such as ROPRO, TorayDS and many more in developing a design of filtration system.

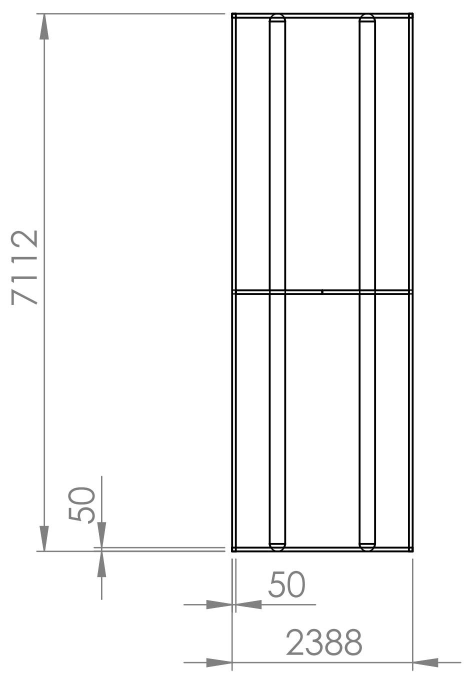
Thus for this project, the information provided in the text book is used as the design basis for the filtration system. In the large scale plant (> $40m^3/h$), 6 to 8 modules per pressure vessel are usually adopted while 3 to 5 modules per pressure vessel for the smaller plant. The Table 5 shows the approximate skid size as a function number of modules per pressure vessel.

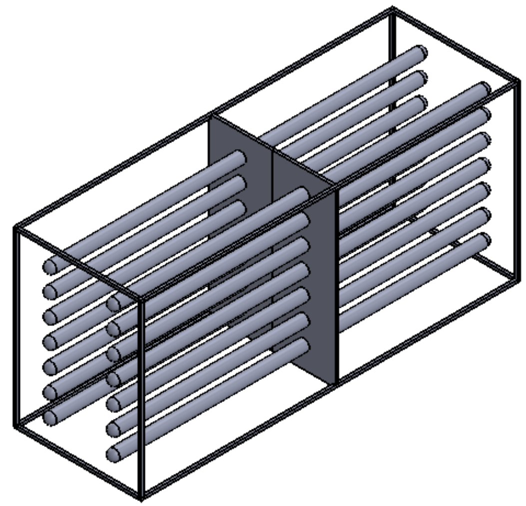
Table 5: The approximate skid dimension **[10]**

No. of modules in series	Length (in.)	Width (in.)	Height (in.)	Array
3	168	32	77-89	3:2:1
4	226	57	80-91	4:3:2 3:2:1 6:4:2
6	280	66	115	8:4 10:5
6	280	94	128	14:7 18:9

As the capacity of filtration system is designed to deliver $265m^3/h$, it is considered as the large scale plan. Thus the filtration skid will consist of six to eight modules. As the information provided in Table 5, the standard practice is the system will consist of six modules with two options of dimension and some choices of array. The technical drawing established as the proposed design solution for the filtration system will have dimension of ($280\times 94 \times 128$)in. The technical drawing is presented in the page 27.







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DRAWN	Faiz Rodzi	16976	3/9/2015
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SHEET 1 OF 1

CHAPTER 5: CONCLUSION AND RECOMMENDATION

In the very beginning, the design concept of the water injection system has been sketched based on the water injection system that has been built in Bokor redevelopment project. A FEED model from Emerson FEED capabilities is adopted in this project in order to demonstrate the FEED work in proposing the design solutions for a water injection system. The FEED model has been scoped to three stages which are FEED planning, data gathering and design basis. The details of each stage are presented in Chapter 4 which begins with identifying the parameters that are going to be solved. Then the data that is required to solve the parameters are gathered and used to solve the parameters. The process of solving the parameters are guided by the selected design basis i.e. Pressure Vessels Design Manual and filtration handbook. The calculated parameters are used to establish the technical drawings as the project deliverables.

It is recommended to precede this project by including all the subsystems involved in the water injection system such as the injection system, piping system and utilities. The output will be better as the estimation will represent the complete system. Besides that, in designing the filtration, the more accurate and proper design could be established if the filtration design software that is available in the market is used such as ROSA Version 6.1 and TorayDS Version 1.1.44.

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APPENDIX

General Vessel Formulas

Part	Stress Formula	Thickness, t I.D.	Thickness, t O.D.	Pressure, P I.D.	Pressure, P O.D.	Stress, S I.D.	Stress, S O.D.
Shell							
Longitudinal [1, Section UG-27(c)(2)]	$\sigma_x = \frac{PR_m}{2t}$	$\frac{PR_i}{2SE + 0.4P}$	$\frac{PR_o}{2SE + 1.4P}$	$\frac{2SEt}{R_i - 0.4t}$	$\frac{2SEt}{R_o - 1.4t}$	$\frac{P(R_i - 0.4t)}{2Et}$	$\frac{P(R_o - 1.4t)}{2Et}$
Circumferential [1, Section UG-27(c)(1); Section 1-1(a)(1)]	$\sigma_\phi = \frac{PR_m}{t}$	$\frac{PR_i}{SE - 0.6P}$	$\frac{PR_o}{SE + 0.4P}$	$\frac{SEt}{R_i + 0.6t}$	$\frac{SEt}{R_o - 0.4t}$	$\frac{P(R_i + 0.6t)}{Et}$	$\frac{P(R_o - 0.4t)}{Et}$
Heads							
Hemi sphere [1, Section 1-1(a)(2); Section UG-27(d)]	$\sigma_x = \sigma_\phi = \frac{PR_m}{2t}$	$\frac{PR_i}{2SE - 0.2P}$	$\frac{PR_o}{2SE + 0.8P}$	$\frac{2SEt}{R_i + 0.2t}$	$\frac{2SEt}{R_o - 0.8t}$	$\frac{P(R_i + 0.2t)}{2Et}$	$\frac{P(R_o - 0.8t)}{2Et}$
Ellipsoidal [1, Section 1-4(c)]	See Procedure 2-2	$\frac{PD_iK}{2SE - 0.2P}$	$\frac{PD_oK}{2SE + 2P(K - 0.1)}$	$\frac{2SEt}{KD_i + 0.2t}$	$\frac{2SEt}{KD_o - 2t(K - 0.1)}$	See Procedure 2-2	
2:1 S.E. [1, Section UG-32(d)]	*	$\frac{PD_i}{2SE - 0.2P}$	$\frac{PD_o}{2SE + 1.8P}$	$\frac{2SEt}{D_i + 0.2t}$	$\frac{2SEt}{D_o - 1.8t}$	*	
100%–6% Torispherical [1, Section UG-32(e)]	*	$\frac{0.885PL_i}{SE - 0.1P}$	$\frac{0.885PL_o}{SE + 0.8P}$	$\frac{SEt}{0.885L_i + 0.1t}$	$\frac{SEt}{0.885L_o - 0.8t}$	*	
Torispherical L/r < 16.66 [1, Section 1-4(d)]	*	$\frac{PL_iM}{2SE - 0.2P}$	$\frac{PL_oM}{2SE + P(M - 0.2)}$	$\frac{2SEt}{L_iM + 0.2t}$	$\frac{2SEt}{L_oM - t(M - 0.2)}$	*	
Cone							
Longitudinal	$\sigma_x = \frac{PR_m}{2t\cos\alpha}$	$\frac{PD_i}{4\cos\alpha\,(SE + 0.4P)}$	$\frac{PD_o}{4\cos\alpha\,(SE + 1.4P)}$	$\frac{4SEt\cos\alpha}{D_i - 0.8t\cos\alpha}$	$\frac{4SEt\cos\alpha}{D_o - 2.8t\cos\alpha}$	$\frac{P(D_i - 0.8t\cos\alpha)}{4Et\cos\alpha}$	$\frac{P(D_o - 2.8t\cos\alpha)}{4Et\cos\alpha}$
Circumferential [1, Section 1-4(e); Section UG-32(g)]	$\sigma_\phi = \frac{PR_m}{t\cos\alpha}$	$\frac{PD_i}{2\cos\alpha\,(SE - 0.6P)}$	$\frac{PD_o}{2\cos\alpha\,(SE + 0.4P)}$	$\frac{2SEt\cos\alpha}{D_i + 1.2t\cos\alpha}$	$\frac{2SEt\cos\alpha}{D_o - 0.8t\cos\alpha}$	$\frac{P(D_i + 1.2t\cos\alpha)}{2Et\cos\alpha}$	$\frac{P(D_o - 0.8t\cos\alpha)}{2Et\cos\alpha}$