Sudan University of Science and Technology

College of Post-Graduate studies

Effect of Corrosion on Steel Storage Oil Tanks

أثر التآكل في خزانات النفط الفولاذية

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بسم الله الرحمن الرحيم

قال تعالى:

{۞ وَقَضَىٰ رَبُّكَ أَلَّا تَعْبُدُوا إِلَّا إِيَّاهُ وَبِالْوَالِدَيْنِ إِحْسَانًا ۚ إِمَّا يَبْلُغَنَّ عِندَكَ الْكِبَرَ أَحَدُهُمَا أَوْ كِلَاهُمَا فَلَا تَقُل لَّهُمَا أُفٍّ وَلَا تَنْهَرْهُمَا وَقُل لَّهُمَا قَوْلًا كَرِيمًا (23) وَاخْفِضْ لَهُمَا جَنَاحَ الذُّلِّ مِنَ الرَّحْمَةِ وَقُل رَّبِّ ارْحَمْهُمَا كَمَا رَبَّيَانِي صَغِيرًا (24) رَّبُّكُمْ أَعْلَمُ بِمَا فِي نُفُوسِكُمْ ۚ إِن تَكُونُوا صَالِحِينَ فَإِنَّهُ كَانَ لِلْأَوَّابِينَ غَفُورًا (25)}

سورة الاسراء

(23-25)

صدق الله العظيم

DECLARATION

I here declare and certify that the ideas, designs and experimental work, results, analyses and conclusion set out in this dissertation are entirely my own effort, except where otherwise indicated and acknowledged.
I further certify that the work is original and has not been previously submitted for assessment in any other course or institution.

Abdulrhamn Abbass Abdulrhman Mohammed

Sign …………………….............................

DEDICATION

To my parents with much love

To my brother and sister

for their inspiration and encouragement

with much gratitude and affection that I can’t well put

down here.

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This research was carried out under the principal supervision of Dr. Hassan Othman. I would like express my great appreciation towards him for his kind, valuable assistance and advice. His vast knowledge and immense expertise in diversified area provided me with working on an industrial project.

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ABSTRACT

Corrosion is one among many degradation mechanisms of steel aboveground oil storage tank structures. Therefore, for tanks in long-term service, a major issue becomes loss of thickness close to, or below, minimum acceptable values, there are many standard and empirical approaches to evaluate the fitness for service of corroded tanks. This study conducted to determine the probabilistic integrity and fitness for service of a bottom plate of an above-ground steel tank by considering the serviceability of the tank as a function of critical thickness profile. The results show that when the coefficient of variation of the measured thickness fall below 10% the fluctuation in thickness through all surface area of the bottom can represent by an averaged value considered the critical thickness. Finite element analysis is conducted to verify the results and, to specify the spots of stress concentration. The remedial action taken is to strengthen the structure by weldment of an annular plates and partial replacement of the plates with minimal thickness. Adopting this procedure result a repair cost saving of 52%, minimizing the downtime to 44.4%, and the rate of return reduced to 49.2%, furthermore a new layout and design basics were made for future construction.

المستخلص

يعتبر التآكل من أحد أشكال التدهور الشائعة في هياكل الخزانات الحديدية لتخزين المنتجات النفطية، لذلك عند المدى الطويل للتشغيل يمثل النقصان في السماكة الى حد أدنى من المستوى المقبول هي إحدى المشكلات الرئيسية ، هناك العديد من الطرق المعيارية والتجريبية المتبعة لتقييم حالة الخزان التشغيلية، إهتمت هذه الدراسة بتقييم حالة أرضية الخزان ،وذلك بأخذ الحالة التشغيلية للخزان كدالة في السمك الحرج للتشغيل، بينت النتائج انه عندما يكون معامل التباين للسمك الذي تم قياسه دون 10%، فان التفاوتات في السمك وعبر كل مساحة أرضية الخزان يمكن تمثيلها بقيمة متوسطة تعبر عن السمك الحرج. استخدمت طريقة العناصر المتناهية الصغر لتوكيد النتائج ولتحديد المواضع التي تتركز عندها الإجهادات، وكانت الإجراءات التصحيحية المأخوذة تقوية أرضية الخزان كانت عن طريق لحام حلقات تقوية والاستبدال الجزئي للمقاطع ذات أقل سمك، و ، باتباع هذه الطريقة ينتج عنه تخفيض تكلفة الصيانة الي 52%، وتقليل الزمن اللازم للصيانة الي 44.4%، ونقصان في الزمن اللازم لاسترداد التكلفة الي 49.2%، إضافة لذلك فإنه تم وضع أسس جديدة لتصميم الأرضيات المراد تنفيذها مستقبلاً.

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ABBREVIATIONS LIST

2-D	Two Dimensions
3-D	Three Dimensions
API	The American Petroleum Institute
ASME	American Society of Mechanical Engineers
AST	Aboveground Storage Tanks
BS&W	Basic Sediment and Water
CI	Cost Index
COV	Coefficient of Variation
CTP	Critical Thickness Profile
FCA	Future Corrosion Allowance
FEA	Finite Element Analysis
FEM	Finite Element Methods
FFS	Fitness for Service
GML	General Metal Loss
HAZ	Heat Affected Zones
HC	Hydrocarbons
LTA	Local Thin Areas
NDT	Non Destructive Testing
NFPA	National Fire Protection Association
ppm	part per million
PTR	Point Thickness Reading
RR	Rate of Return
TK-7	Tank Number seven
TK-8	Tank Number eight

UFC	Uniform Fire Code
USD	United States Dollars

CHAPTER ONE

INTRODUCTION

1.1. PREFACE

In this modern and competitive world, refined petroleum products storage and handling companies worldwide are under pressure to maintain products quality and safety standards high with minimum losses and spills at strict level of environmental friendly operations conditions, these always restricted by economic considerations including but not limited to infrastructure, transportation and the management of the supply chain for the whole downstream sector from the refinery till the customers.

The aim of this study is to investigate at the structure level the problems of defects at the bottoms of Aboveground Storage Tanks (AST) that produced due to corrosion. The objective is to set an approach to predict the conditions considered minimum for fitness for service by study and evaluating the severity of the defects and suggest with aid of computer application a solution/s and remedies to raise up the overall facility production cycle performance.

Various industrial engineering technique and tools are implementing in this study in order to investigate and solve the problem that occurs in the plates of the bottom. Finite Element Analysis FEA package ANSYS for modelling and analysis will be applied to this study. Inspection data for the selected area are collected, studied and analyzed. The defects with the highest failure probability will be the main target to be improved. Various causes of the defects will be analyzed and various solving method will be present.

1.2. PROBLEM STATEMENT

leaks of stored products from the bottom of AST may occur for variety of causes, at design and construction stage poor joints at adjacent plates, bad welding procedure/practice which in terms initiate local weak spots and non-uniform thermal stresses distribution, seismic effects in addition to the operations conditions itself (repeated loading unloading processes).

software such as ANSYS, with its simulation Packs could be used for drafting, generating and, analyze the selected model and thus it could be possible to identify and predict and verify the effect of the defects which are the study scope. This study tries to identify and predict the impact of corrosion defects occurs at the base (bottom plates) of AST and hence overcome and reduce the serviceability and improve the norms of operations of for future.

1.3. OBJECTIVES

The main purposes in accomplishing this study are shown below:

1) to set a detecting and resolving approach of base corrosion defects occur in steel tanks in bulk storage/handling industry.

2) to identify the highest probability of defects occurs at the bottom.

3) to determine and evaluate of remedial alternatives regarding the economic prospects.

4) to implement FEM tools for the selected tank to specify the spots of stress concentration.

1.4. SCOPES

The scope of this study is mainly focusing on the criteria shown below:

a) Using the Coefficient of Variation (COV) approach to evaluate the fitness for service level.

b) The study mainly focuses on AST but only selected part (bottom) are considered with check sheets, charts, and related design and inspection data.

c) The industry that will be select is limited to refined petroleum products marketing and Distribution sector with premises for storage and handling.

d) Only defects at the selected parts will be analyzed.

e) Sample model being analysis 5000m^3 AST with diameter of 24.38m and height of 13.5m dome roof free vent type.

1.5. METHODOLOGY

The study was conducted by collecting and checking the data of the tank (basic design data) including the materials of which the plates are made, the parametric data regard the construction (welding parameters), the operation conditions i.e. specifications of stored product/s, and, the computer application modules necessary for generation of tank model that include all parameters considered for analysis.

The following situations/issues arise through the progress of the study conduction:

- Lack of records for similar cases. Some data of the model considered highly confidential regarding the operational and design parameters, in a such situations assumptions would be made upon codes, standards and, recommended practices.

- The computer applications for such type of studies are costly and need advanced level of practicing, many educational versions of the software cover only certain modules, thus its necessary to use many applications to conduct the overall study.

CHAPTER TWO

LITERATURE REVIEW

2.1. PREFACE

This Chapter reviews briefly the basic theories associated with tank analysis and design. Since tanks are basically thin cylindrical shells, the basic shell theory is presented here. A brief summary of failure theories, basics of beam-on-elastic foundation theory and concepts of corrosion and corrosion analysis are presented. Pertinent concepts about fitness for service procedures and their application to storage tanks are introduced. The concept of limit analysis, limit load the estimation of remaining strength factor of damaged tanks used for analysis are also explained. A survey of previously reported research works relevant to the scope of current research is included.

2.2. TYPES OF TANKS

There are many different forms to classify storage tanks in the next paragraphs a general idea of the basis upon which the storage tanks classification implemented are briefly illustrated.

2.3. ABOVE- AND BELOW-GROUND TANKS

The generic and most fundamental classification is based upon whether they are above or belowground. The aboveground tanks have almost all their structure exposed. The bottom part of these tanks is placed directly over soil or on a concrete foundation.

The majority of the steel tanks observed during the field trips were found to be built on concrete foundations. Advantages of this type of tank includes that they are easier to construct, can be built in far larger capacities than underground storage tank, and costs less than those built underground. A less common class of aboveground tanks supported by columns or frames is called elevated tanks. They are almost exclusively employed by municipal water supply companies.

Underground tanks have less capacity than aboveground tanks and are usually limited to between 20,000 and 75,000 liters (5,000 and 20,000 gal) with most being less than 45,000 liters (12,000 gal) [1]. They require special considerations for the earth loads to which they are subjected, because of their contents. Underground tanks store fuels as well as a variety of chemicals. Another aspect to consider is buoyancy, because they are anchored into the ground, they should not be able to pop out during periods when ground water surrounds the tank. In addition, because they are underground, they may be subjected to severe corrosion.

For the purpose of this work, attention is restricted to aboveground tanks, for which structural integrity is an important design consideration for safe and stable operational loads.

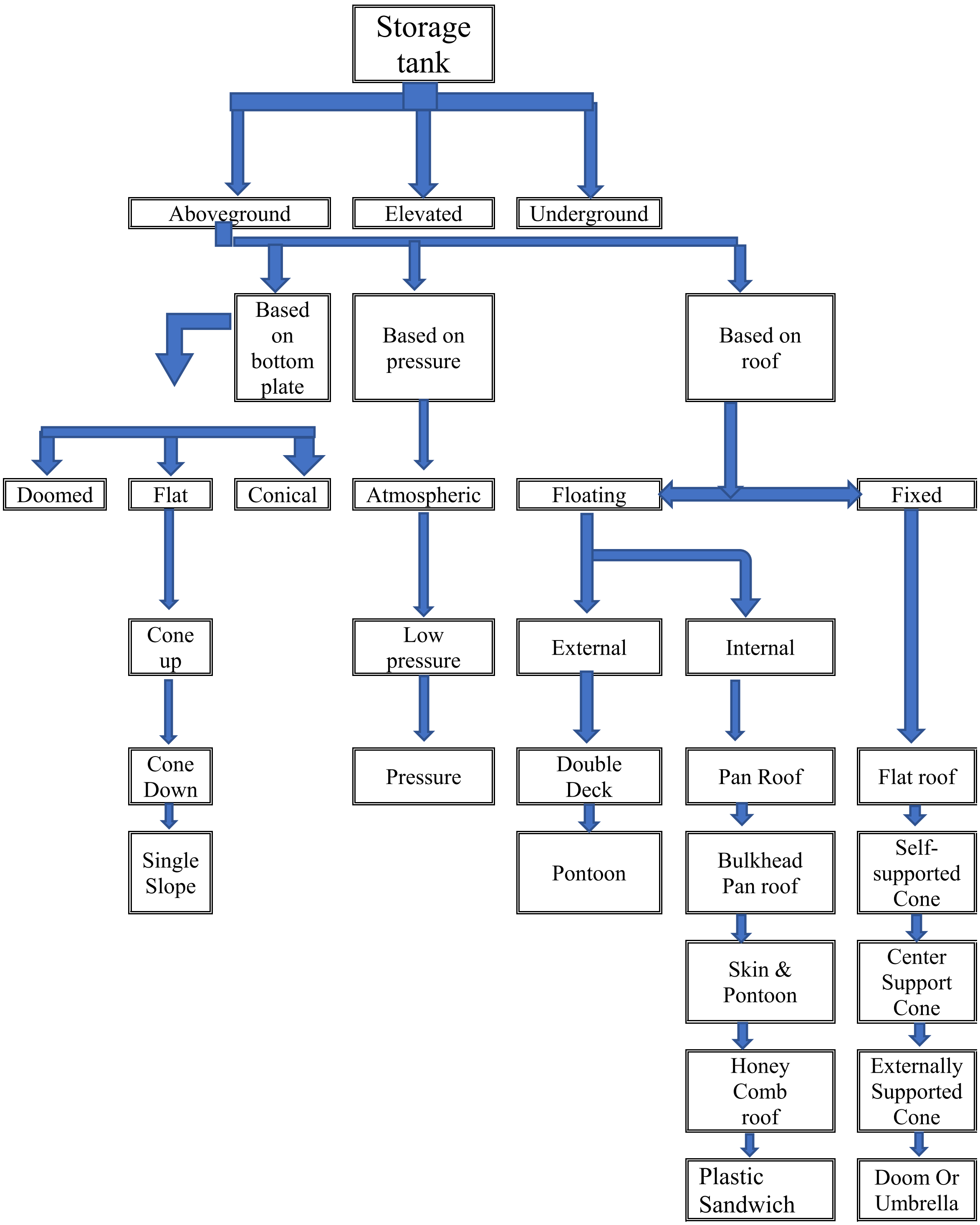


Figure 2-1: Classification of storage tanks.

2.4. CLASSIFICATION BASED ON THE INTERNAL PRESSURE

In the case that an internal pressure acts on the tank during storage, the classification will be on this level of pressure. This pressure effect depends directly of the size of the tank. The larger the tank, the more severe effect of pressure is on the structure. This classification is commonly employed by codes, standards and regulations all over the world.

2.4.1. ATMOSPHERIC TANKS

These tanks are the most common. Although they are called atmospheric, they are usually operated at internal pressure slightly above atmospheric pressure. The fire codes define an atmospheric tank as operating from atmospheric up to 3.5 KN/m^2 above atmospheric pressure [2].

2.4.2. LOW-PRESSURE TANKS

Within the context of tanks, low pressure means that tanks are designed for a pressure higher than atmospheric tanks. This also means that these tanks are relatively high-pressure tanks. Tanks of this type are designed to operate from atmospheric pressure up to about 100 kN/m^2 [1] [2].

2.4.3. PRESSURE VESSELS (HIGH-PRESSURE TANKS)

Since high-pressure tanks are really pressure vessels, the term high-pressure tank is not frequently used; instead they are called only vessels. They are treated separately from other tanks by all codes, standards, and regulations.

2.5. CLASSIFICATION ACCORDING TO MAJOR TANK COMPONENTS

There is no simple way to classify tanks based upon a single criterion such as its shape or roof. But this criterion is easier than any other one because tanks are classified only by visual observation. The shape is usually determined by the contents. The vapor pressure of the substance stored or internal design pressure is the broadest and most widely used method adopted by codes, standards and regulations, as explained above. For this reason, the vapor pressure determines the shape and, consequently, the type of tank used. These major tank components include the general shape of the tank and the roof shape itself.

2.5.1. THE ROOF OF A TANK

The shape of the roof is a useful indicator of the type of a tank because it is self- explanatory to tank designer, fabricator and erector.

2.5.2. FIXED-ROOF TANKS

A shallow cone roof deck on a tank approximates a flat surface and is typically built of 4.76 mm thick steel [2].Most aboveground tanks have cylindrical shapes on the part that contains fluids. The cylinder is an economical, easily fabricated shape for pressure containment. An important feature of such cylindrical tanks is that the top end must be closed. As discussed before, the relatively flat roof and bottom or closures of tanks do not lend themselves to much internal pressures. As internal pressure increases, the tank designers use domes or spherical caps.

2.5.3. CONICAL ROOF

Cone-roof tanks have also cylindrical shells in the lower part. As illustrated in figure 2-2, these are the most widely used tanks for storage of relatively large quantities of fluid. The tanks that we will study in the following chapters are of this type. They have a vertical axis of symmetry, the bottom is usually flat, and the top is made in the form of shallow cone. They are economical to build and the economy supports a number of contractors capable of building them. Cone-roof tanks typically have roof rafters and support columns except in very small-diameters tanks.

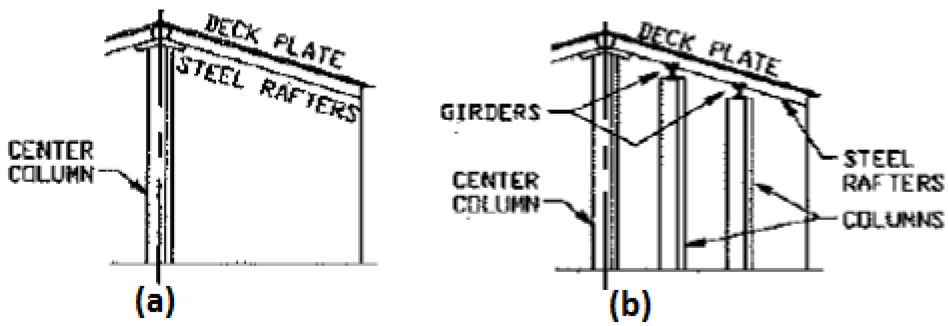


Figure 2-2: (a) Center supported cone roof, and, (b) supported cone roof.

2.5.4. UMBRELLA-ROOF TANKS

They are very similar to cone-roof tanks, but the roof looks like an umbrella. They are usually constructed with diameters not much larger than 20 m. Another difference is that the umbrella-roof does not have to be supported by columns to the bottom of the tank, so that they can be a self-supporting structure.

2.5.5. DOME-ROOF TANKS

This type has almost the same shape of the umbrella type except that the dome approximates a spherical surface more closely than the segmented sections of an umbrella-roof as shown in figure 2-3, there are several ways to fabricate such tanks. One of them is known as the tank airlift method, “in which the roof and the upper course of shell are fabricated first, then lifted by air that is blown into the tanks as the remaining lower courses of steel shell are welded into place [3].

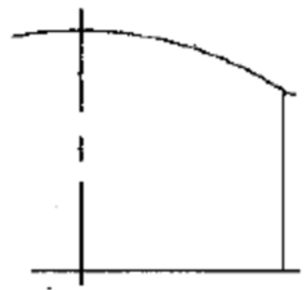


Figure 2-3: Dome roof tank.

2.6. TANK BOTTOMS

Another important component of tanks are the bottoms made of welded steel plates. In the analysis, tanks are usually modeled as fixed to the ground, so that it is not a problem to know exactly the shape of the bottom. But for the designer this aspect is very important because of the varying conditions to which a tank bottom may be subjected. A tank bottom may be broadly classified as flat bottom or conical.

2.6.1. FLAT BOTTOM

They are the most common end closures of tanks. These tanks appear flat but usually have a small designed slope and shape. These tanks are sub classified according to the following categories:

2.6.2. FLAT

For tanks less than about 6-9 m in diameter, the flat-bottom tank is used. The inclusion of a small slope as describe above does not provide any substantial benefit, so they are fabricated as close to flat as possible as illustrated in figure 2-4.

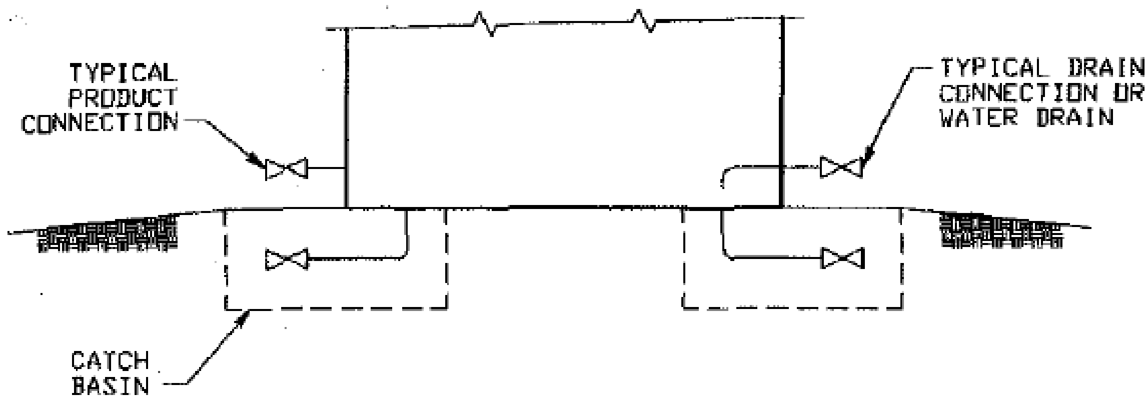


Figure 2-4: Flat bottom tank.

2.6.3. CONICAL BOTTOM

The second type is the conical bottom. The designers often use it to provide a complete drainage or even removal of solids. Since these types of tanks are costlier, they are limited to the smaller sizes and are often found in the chemical industry or in processing plants.

2.6.4. CONE UP

These bottoms are built with a high point in the center of the tank. Crowning the foundation and constructing the tank on the crown accomplish this. The slope is limited to about 25 to 50 mm per 3 m run as shown in figure 2-4 below.

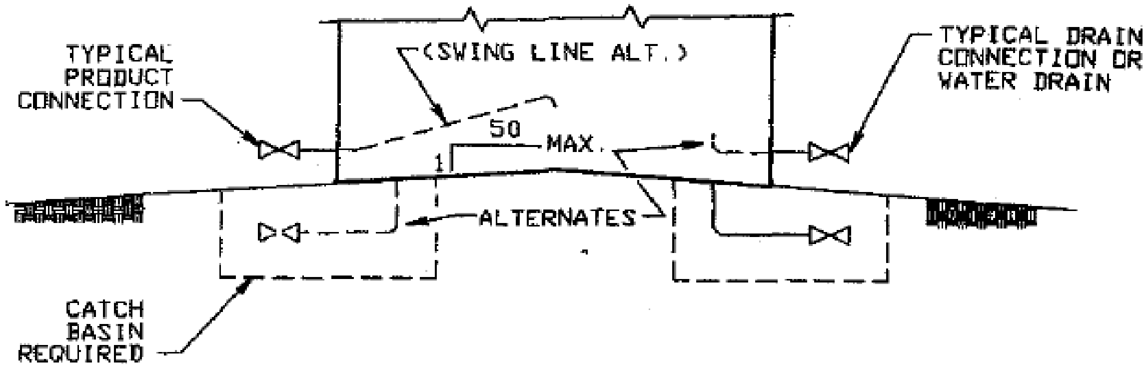


Figure 2-5: Cone up steel storage tank bottom.

2.6.5. CONE DOWN

The cone-down design slopes toward the center of the tank as in figure 2-5. Usually, there is a collection sump at the center. It is very effective for water removal from tanks. This design is inherently more complex because it requires a sump, underground piping, and an external sump outside the tank.

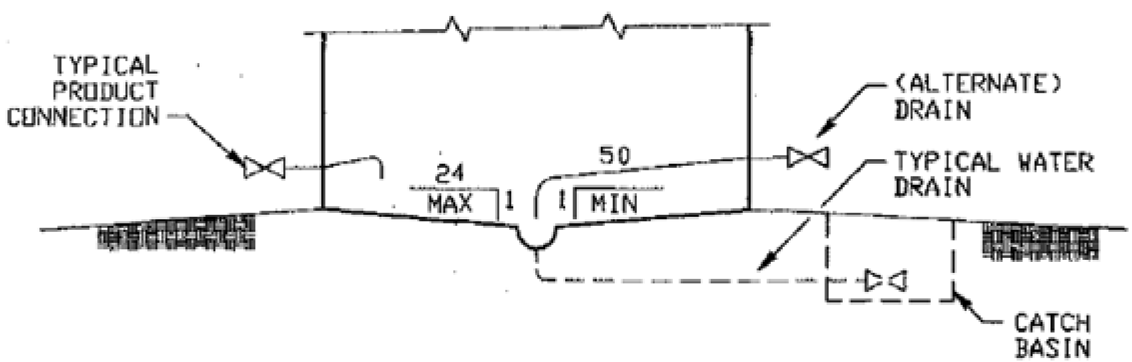


Figure 2-6: Cone down bottom with sump.

2.6.6. SINGLE SLOPE

This design uses a planar bottom but it is tilted slightly to one side. This allows for drainage to be directed to the low point on the perimeter, where it may be effectively collected, this could be clearly seen in figure 2-6. Since there is a constant rise across the diameter of the tank, the difference in elevation from one side to the other can be quite large. Therefore, this design is usually limited to about 30 m.

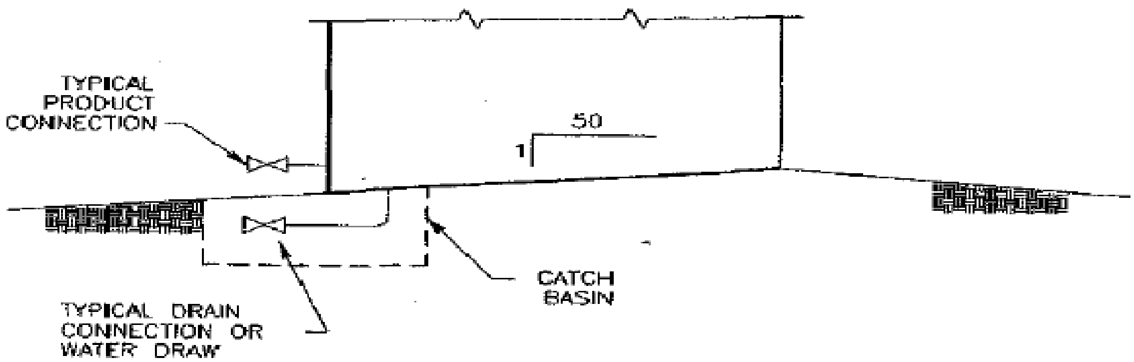


Figure 2-7: storage tank with a single slope bottom.

2.6.7. FOUNDATIONS OF TANKS

In many cases (especially for tanks located in coastal areas) the soils are susceptible to have uniform or differential settlements, while it is difficult to classify all possible foundation types for storage tanks, some general types have proved to be most common for specific applications. Foundation types may be broken into several classifications in generally increasing order of costs.

2.6.8. COMPACT SOIL FOUNDATIONS

These foundations can be used where the soil quality and bearing capacity are good. Generally, the top 7 to 15 cm of soil is removed and replaced with a sand or granular backfill. These are often called sand pad foundations, laid directly on earth. The advantage of this type of foundation is the relatively low cost.

2.6.9. CONCRETE RING-WALL FOUNDATIONS

The concrete ring-wall foundation is so called because of its appearance. It is used in foundations for tanks of a diameter of at least 10 m or more, this is usually the most cost-effective reinforced concrete foundation, with many advantages such as reducing the probabilities of settlements failures.

2.6.10. CRUSHED-STONE RING-WALL FOUNDATIONS

This design happens to incorporate a leak detection system. While it costs less than the concrete ring-wall, it has many of the advantage of the concrete ring-wall. It provides uniform support of the tank bottom by dissipating concentrated loads in a granular pattern. Catastrophic failure of the bottom is possible if a leak starts and washes out the underlying support.

2.6.11. SLAB FOUNDATIONS

The concrete slab foundation has the advantages of the concrete ring-wall but is usually limited to tanks with diameters less than 10 m. Often the edge of the slab will be sufficiently thick to provide for anchorage. A slab foundation is very versatile, but its high cost limits it to use in small tanks. The slab provides a level and plane-working surface that facilitates rapid field erection.

2.6.12. PILE-SUPPORTED FOUNDATIONS

The pile-supported foundation is usually found where the soil bearing pressures are very low. Examples might be river deltas and land adjacent to bays. They are also used where high foundation uplift forces are encountered resulting from internal pressure or seismic loading.

2.6.13. MATERIALS OF CONSTRUCTION OF STORAGE TANKS

Tanks are constructed from a number of different materials based upon the availability and cost of the material, ease of fabrication, resistance to corrosion, compatibility with the fluid stored. Sometimes specialized composites and techniques are used in tank construction, but these are the exception.

2.6.14. CARBON STEEL

Or mild steel, is by far the most common material for tank construction in Sudan. This material is readily available, and because of the ease with which it is fabricated, machined, formed, and welded, it results in low overall costs. The material properties most commonly assumed for modeling are a modulus of elasticity of 207 GPa, Poisson's ratio of 0.3, mass density of 7849.7 kg/m^3, and yield strength of 215 GPa.

2.6.15. STAINLESS STEEL

Usually the austenitic group of stainless steels, is an important material used for storage of corrosive liquids. Although the material cost is significantly more than that of steel, it has the same ease of availability as carbon steel.

2.6.16. FIBERGLASS REINFORCED POLYMERS

This type of tanks are noted for their resistance to chemicals where stainless steel or aluminum tanks are not acceptable. However, the fabrication and construction techniques are somewhat more specialized than those for metals fabrication.

2.6.17.ALUMINUM

This type of tanks is suitable for a limited number of materials. It is the less common metal used to build tanks. These tanks remain ductile at temperatures much lower than those of carbon steel. However, nickel steels and stainless steels have largely supplanted the market for aluminum tanks.

2.6.18. CONCRETE

This type has been used in the water and sewage treatment for a long time. However, they are outside the scope of this work.

Tanks made of metal materials such as carbon steel, stainless steel and aluminum are very prone to failure under natural hazards. Carbon steels used for storage tanks have specified minimum yield strengths of approximately 200 to 400 GPa. The principles of material selection are subdivided in the following engineering considerations, such as experience, code requirements, brittle fracture and corrosion.

2.7. CODES AND DESIGN CONSIDERATIONS

The purpose of standards and codes is providing acceptable, practical, and useful guidance that ensure quality, safety, and reliability in equipment, practices, operations, or designs. which can be generally expressed as a category of one of the following basic categories:

2.7.1. STANDARDS

These are considered to be mandatory practices that must be complied with, so that the equipment manufactured may be considered in compliance or may be marked as complying with the standard. Standards are also often called codes.

2.7.2. RECOMMENDED PRACTICES

These are advisory documents that provide technological background and practices, which may be useful for the specific application at hand. They are not mandatory.

2.7.3. PUBLICATIONS OR BULLETINS

These are primarily for the purpose of informing the user of general aspects of the industry technology or practices.

2.7.4. SPECIFICATIONS

They are considered interchangeable with standards. Specifications may also be a component of standards or codes.

Many organizations have contributed in some way to storage tank technology. The most important ones are:

- The American Petroleum Institute (API).
- American Society of Mechanical Engineers (ASME) [4].

The fire protection organizations and codes (application and jurisdiction of U.S. fire codes): Uniform Fire Code (UFC) and National Fire Protection Association (NFPA).

2.8. CORROSION IN ABOVEGROUND STORAGE TANKS

Corrosion has been shown to be the cause of 15-20% of leakages of hydrocarbons from offshore plant. Leakages can lead to more disastrous consequences if subsequent ignition was to result in fire or explosion. In order to reduce the number of leakages from this source, the defects that lead to failure need to be detected and mitigating action taken before failure occurs. The refinery products containing mixtures of straight-chain and branched chain hydrocarbons, alkenes, naphthalene's, aromatics, and other compounds Oil derivatives should not be corrosive to metals. The accumulation of water at the bottom of storage tanks is a primary prerequisite for development of corrosion. Generally, it is extremely difficult to avoid the presence of water in tanks. The basic sediment and water (BS&W) content in storage and transport facilities is usually limited to 0.5 volume percent [5]. However, water and water vapors may ingress storage, transportation, and some other operations [6] .

Because of the high polarity of water molecules, the water drops separate from the organic phase on the steel surfaces forming a water pillow at the bottom of the tanks and electrochemical corrosion of steel takes place. Processes of bottom corrosion may proceed even more intensively due to upper inflow of oxygen into the tanks [7].The solubility of oxygen in hydrocarbons is higher (60 to 70 ppm) than in water (8 ppm). Therefore, oxygen diffuses from the organic phase (hydrocarbons or fuel) to the water phase according to the solubility in each phase, and the concentration gradient increases up to oxygen saturation in the aqueous phase [7].

Concentration cell corrosion may occur when a surface deposit, mill scale, or crevice creates a localized area of lower oxygen concentration [8]. The difference in oxygen concentration between the inaccessible area and the bulk electrolyte creates a concentration cell and may result in significant localized metal loss.

The extent of internal corrosion is also influenced by the temperature, CO_2, H_2S and salts (sodium chloride, calcium chloride, and magnesium chloride), light organic acids, etc. In storage tanks, the aggressive variables undergo diversion from organic phase into the aqueous phase and may cause a decrease in the pH and increase in the water corrosivety. Even when some biotic corrosive factors are absent, the bacteria are known to cause severe internal corrosion problems in oil storage and transport [9].
Ability of micro-organisms to live and make colonies in both the water phase and the inter-phase of water/hydrocarbon, as well as the generation of their metabolism products which made the physical and chemical properties of the stored product worse.

Activity of microorganisms promotes an increase of suspended solids content and formation of corrosive sludge at the bottom of tanks. Microbial degradation of HCs and other organic compounds increases the water content in sludge, which can exceed 10%. Pitting corrosion has been observed underneath sludge deposits that are a mix of sand and clay particles, water, and product [5].

Another corrosion formation Scenario occur on the bottoms of tanks by the flushing operation when the stored product is intended to be replaced with another different, the adopted procedure is to use the sea water for lines flushing due to repeated, frequent pitting between the solids in the flushing water and the surface of the bottom which in turn, scratches and removes any protective layer and a rust scale formed on the bottom surface.

As loading /unloading processes proceed corrosion at the location on the floor plates spreads where the coating and/or any protective rust scale has been damaged. In some cases, the welding processes produce variances in the microstructure of the steel bottom plates which impact in a galvanic corrosion as a result occur at the heat affected zones (HAZ) of the base near the weldments locations.

2.8.1. STUDIES RELATED TO CORROSION IN STORAGE TANKS

Corrosion is in essence a statistical effect governed by a number of variables. For example, microscopic variations in a surface tend to cause different forms of corrosion and also variations in the corrosion rate over either a wide or small area (pitting). In these areas the simple assumption that corrosion rate is uniform across an area is unlikely to be accurate, and sample thickness measurements are unlikely to be representative of the whole component. Studies and applications of the statistical nature of corrosion and its relationship to inspection, have been carried out since the 1950's, but have never been commonly applied in routine inspections. No standards exist for the analysis of inspection data for corrosion.

Initial work using extreme values was carried out by Gumbel [10].He used the theory to estimate the condition of pipelines with external corrosion. Manley [11]described the use of an ultrasonic thickness gauge, and a computer, to log and record data from an erosion/corrosion survey. Essentially the method used was linear interpolation of sample readings.

Joshi et al [12]use the extreme value analysis method to extrapolate from small inspection patches in an above ground storage tank to the whole tank. They noted that the method particularly applied to pitting corrosion. Sparago [13]shows how the underlying thickness distribution can be used to estimate the probability of a wall thickness being below a certain level from ultrasonic thickness gauge data.

Kawaka [14]gives a useful overall text to the statistical method of analyzing corrosion data. The use of these methods for analyzing corrosion data has been referred to consistently in Japan since the 1980's, however little of the work refers to the strategies of data collection by NDT methods.

More recently Mitsui Babcock [15]conducted a group sponsored project which included some analysis of corrosion data by the extreme value method.

Thus it can be seen that although the statistical methods have been developed, the application of these methods is not carried out routinely apart from possibly in Japan. The works above, although describing the methods used, do not generally validate the results obtained by comparing a sample with the whole population.

2.9. THEORIES OF FAILURE

Structural members subjected to loads may fail to perform their intended function in various ways. Depending on the loading, geometry and material properties they may fail because of excessive deformation, material yielding, fracture, instability, etc. Yielding of the material is an important mode of failure in many components.

In his survey and analysis for the cases of failure due to tanks rupture at international scale for the period from1964 To 2004 Cheng [16]found that most storage tank damage is attributable to corrosion ,age deterioration and ,seismic motions. damage usually occur at the bottom plates or the welding edges. Both crude oil spills from storage tanks into bunds at a Kaohsiung, Taiwan refinery in 2002 and at a Fawley, Hampshire, UK refinery were caused by the corrosion of tank bottom [17].

The corrosion of a defective weld was attributed to a 1999 spillage of 12 tonnes of sodium cyanide solution from a Cleveland, UK storage tank into the ground and river tees [17].The 1977 incident at an Umm Said, Qatar gas processing plant was caused by a weld failure of a 260,000-barrel tank containing refrigerated propane at K45 degree Fahrenheit.

The failure of the bottom portion of a newly fabricated tank containing hydrochloric acid at an Illinois lighting plant in 2001 was probably due to mal-fabrication [18].

A crack of a storage tank at a Floreffe, Pennsylvania terminal in 1988 released 92,400 barrels of diesel oil into the river [19]and a 1974 crack at the bottom plate of a tank at a Mizushima port, Japan refinery released 7500,000 liters of heavy oil into the sea [20]The tidal wave carried thousands barrels of crude oil into the river, after 4 storage tanks ruptured at a Lima, Ohio refinery in December 1983 [21].

The Umm Said, Qatar incident that resulted in an 8-day fire and property damage over 100,000,000 dollars is the largest property damage loss caused by the crack [22]In 1993, an operator at a Kaohsiung, Taiwan refinery fell off from a rust hole on the roof into the tank [23].

2.9.1. CRITERION OF STRESS - STRAIN IN TANK STUDIES

For unidirectional stress field, the yield strength obtained from a standard uniaxial test can be the criterion. But for multi-axial state of stress, the yielding is governed by some quantity representing the state of strain, stress, components of strain energy, etc. Hence, the yield criterion is usually being the state of stress and implies that yield boundary has been reached and indicates that the stress state is elastic.

The yield function is developed such that the components of multi-axial stress can be combined in to a single quantity and termed as effective stress which then compared with the yield strength (obtained from uniaxial test), in some appropriate form, to determine if yield has occurred. The following are some of the yield criteria that are often used in engineering practice.

2.9.2. MAXIMUM SHEAR STRESS CRITERION

The maximum shear-stress criterion, also known as the Tresca criterion, states that yielding begins when the maximum shear stress at a point in the structure equals the maximum shear stress at yield in uniaxial tension (or compression). The maximum shear stress (τ_{max}) is given by half of the difference between maximum and minimum principal max stress components. In ductile metals, the crystals have slip planes along which the resistance to shear force is the weakest. Hence yield criterion based on shear stress is more appropriate for ductile metals. The Tresca criterion generally gives conservative results for metals. Because it is simple to use, many engineers and codes (e.g., ASME) prefer it for metal structures. The yield surface for this criterion is a regular hexagon in 2D principal stress space as shown in Figure 2-8.

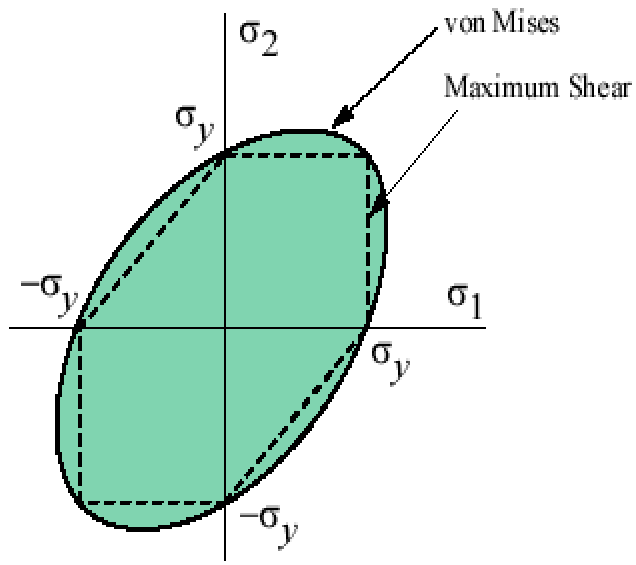


Figure 2-8: Von Mises vs Tresca criteria

2.9.3. DISTORTIONAL ENERGY DENSITY CRITERION

This criterion, also referred as von Mises criterion or octahedral shear stress criterion states that yielding begins when the distortional strain energy density at a point in the structure equals the distortional strain energy density at yield in uniaxial tension (or compression). Figure 2-9 ,the plate stresses are listed for the top and bottom of each active plate. The principal stresses sigma1 (σ_1) and sigma2 (σ_2) are the maximum and minimum normal stresses on the element at the geometric center of the plate.

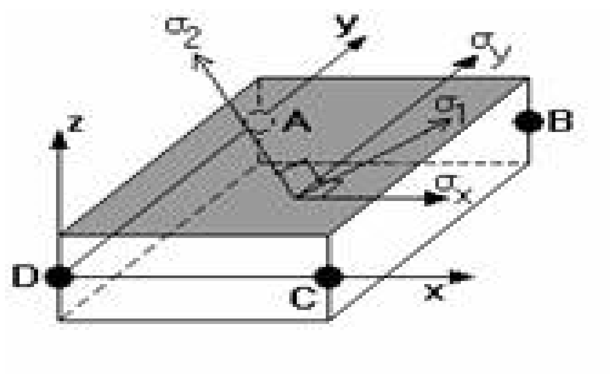


Figure 2-9: Plate principal Stress

The Tau Max (τ_{max}) stress is the maximum shear stress. The Angle entry is the angle between the element's local x-axis, and the direction of the σ_1 stress (in radians). The Von Mises value is calculated using σ_1 and σ_2, but not σ_3 which isn't available for a surface (plate/shell) element, so this Von Mises stress does not include any transverse shear forces. The equations are:

$$\sigma_1 = \frac{(\sigma_x+\sigma_y)}{2} + \sqrt{\frac{(\sigma_x-\sigma_y)^2}{4} + \tau_{xy}^2} \tag{2.1}$$

$$\sigma_2 = \frac{(\sigma_x+\sigma_y)}{2} + \sqrt{\frac{(\sigma_x-\sigma_y)^2}{4} + \tau_{xy}^2} \tag{2.2}$$

$$\tau_{max} = \frac{(\sigma_1+\sigma_2)}{2} \tag{2.3}$$

$$\Phi = \frac{1}{2}arctan\left|\frac{2\tau_{xy}}{(\sigma_x-\sigma_y)}\right| \tag{2.4}$$

$$VonMises = \sqrt{\sigma_1^2 - (\sigma_1 * \sigma_2) + \sigma_2^2} \tag{2.5}$$

Where,

$\boldsymbol{\sigma_1}$ = *Maximum normal stresses on the element at the geometric center of the plate.*

$\boldsymbol{\sigma_2}$= *Minimum normal stresses on the element at the geometric center of the plate.*

$\boldsymbol{\tau_{max}}$= *Maximum shear stress.*

Φ=The angle in radians between the maximum normal stress and the local x-axis.

The angle, Φ, is the angle in radians between the maximum normal stress and the local x-axis. The direction of the maximum shear stress, t_{max}, is ± π/4 radians from the principal stress directions.

The Von Mises stress is a combination of the principal stresses and represents the maximum energy of distortion within the element. This stress can be compared to the tensile yield stress of ductile materials for design purposes. For example, if a steel plate has a tensile yield stress of 36 *Mpa*, then a Von Mises stress of 36 *MPa* or higher would indicate yielding of the material at some point in the plate.

The σ_x , σ_y , and σ_{xy} values used to calculate the stresses are a combination of the plate bending and membrane stresses, thus the results are considered for the top and bottom surfaces of the element. The “Top” is the extreme fiber of the element in the positive local z direction, and the “Bottom” is the extreme fiber of the element in the negative local z direction. The membrane stresses are constant through the thickness of the element, while the bending stresses vary through the thickness of the element, very similar to the bending stress distribution in a beam.

The von Mises or Tresca criteria are more suitable for ductile metals and predict the initiation of yielding quite well and are the most popular and hence are presented here. shown on the figure 2-8 is the maximum shear stress criterion (dashed line). This is more conservative than the von Mises criterion since it lies inside the von Mises ellipse and the von Mises criterion is slightly more accurate than Tresca criterion and has a smooth profile unlike the Tresca function.

Since the von Mises yield function is continuously differentiable, it is preferred in computational plasticity studies in which plastic flow and strain hardening are considered. Similarly, there are many other theories of failure suitable for different types of materials. The current work uses von Mises exclusively.

2.10. SHELL THEORY

In the present research, vertical Aboveground Storage Tanks (AST) of cylindrical shape are studied. The theory of cylindrical shells is used in the analysis and design of AST. Hence a brief summary of this theory is presented here. Detailed analysis of this theory is presented by many authors e.g.Timoshenko and Woinowsky-Kreiger [24].

2.10.1. BEAM-ON-ELASTIC FOUNDATION

Beam-on-elastic foundation theory is used to analyze structures that can be idealized as a beam of relatively low stiffness placed on a flexible foundation and loads are applied on the beam.

This theory finds applications in a variety of practical engineering problems like a rail road placed on soil subgrade, floor systems with beams (as used in ships), buildings, bridges and components made of thin shells of revolution like tank walls, boilers, etc. In ASTs, this theory is also used to determine the minimum length of the annular plate the fatigue life of the shell to bottom joint of tanks, etc. The theory is based on the assumption that the reaction forces of the foundation are proportional at every point to the deflection of the beam at that point. The vertical deformation characteristics of the foundation are defined by means of identical, independent, closely spaced, discrete and linearly elastic springs. The constant of proportionality of these springs is known as the modulus of sub grade reaction (K).

The Winkler model, which has been originally developed for the analysis of railroad tracks, is very simple and does not accurately represent the characteristics of many practical foundations. One of the most important deficiencies of the Winkler model is that a displacement discontinuity appears between the loaded and the unloaded part of the foundation surface. In reality, the soil surface does not show any discontinuity as shown in Figure 2-10(b).

Figure 2-10: (a) Winkler Foundation (b) Practical Soil Foundations

Various models have been proposed by researchers to overcome this deficiency in Winkler's model by introducing the interactions between the individual springs using interconnecting elements like beams or plates.
In the model proposed by Hetényi [25]interaction between the independent spring elements is accomplished by incorporating an elastic beam (2-D) or an elastic plate (3-D), that can deform only in bending.

2.11. FITNESS FOR SERVICE EVALUATION

In the case of above ground storage tanks, a typical tank may cost of dollars to construct/replace and a substantial portion of that would be needed for repair and rehabilitation [26].

In addition to the cost, issues concerning logistics, environmental impact, effect on the process cycle due to out of service tanks, safety permits, etc., cause huge losses in resources and time that cannot be exactly accounted for. If the tank fails by flooding, explosion, etc., it creates a severe impact on the environment and the surrounding community.

It sets in a series of crisis like situations at multiple levels adversely affecting the lives of the population [27]Hence, periodic inspection of the tanks for structural health and safety is a part of the engineering duties. The engineer is expected to periodically monitor the structural health and integrity, asses the degradation and take decisions regarding repairs/replacement.

Fitness for service assessments are the primary methods to do the task. They are quantitative and qualitative engineering evaluations performed to assure the structural integrity of an in-service component with damage, determine the remaining life of degraded components and make run/repair/replace decisions.

Common reasons for assessing the fitness for service of equipment include the discovery of a flaw such as a locally thin area or crack or corrosion, settlements, failure to meet current design standards, and plans for operating under more severe conditions than originally expected. Fitness for service assessment applies analytical methods to evaluate flaws, damage, and material aging.

The analytical methods are based on stress analysis, but they also require information on equipment operations, nondestructive examination (NDT), and material properties. Stress analysis can be performed using standard handbook or design code formulas or by means of finite element analysis (FEA), which is increasingly becoming more common. The main results of the assessment are :

- facilitate to decide whether to run, alter, repair, monitor, or replace the items assessed and,
- Setting points for inspection interval for the equipment.

Fitness for service assessment requires both knowledge of past operations conditions and, a predicts of future conditions. American Petroleum Institute (API) codes of practice API 579-1/ASME [28]and, FFS-1/653 [29] provide a detailed procedure for assessing fitness for service in tanks.

2.11.1. LEVELS OF FITNESS FOR SERVICE ASSESSMENT

Three Levels of assessment are provided in API 579-1/ASME FFS-1 standard. In general, each assessment level provides a balance between conservatism, the amount of information required for the evaluation, the skill of the personnel performing the assessment, and the complexity of analysis being performed. Level I is the most conservative, but is easiest to use. Practitioners usually proceed sequentially from a Level I to a Level III analysis (unless otherwise directed by the assessment techniques) if the current assessment level does not provide a clear result, or a course of action cannot be determined.

2.11.2. LEVEL I ASSESSMENT

The procedures in this level are intended to provide conservative filtering criteria that can be utilized with a minimum amount of inspection or component information, it may be performed either by plant inspectors or engineering personnel. The only load considered is internal pressure, and a single thickness with one or two surface area dimensions are used to characterize the local metal loss. Level I assessments are limited to components covered by a recognized code or standard which have a design equation that specifically relates pressure (or liquid fill height for tanks) to a required wall thickness. Hence it is not applicable for complex loading or damage conditions.

2.11.3. LEVEL II ASSESSMENT

The assessment in this level are intended to give a more detailed evaluation that produces results that are more precise than those from a Level I assessment. Where here, inspection information similar to that of Level I assessment is needed; however, more detailed calculations are used in the evaluation. More general loading is considered (e.g. net-section bending moments on a cylindrical shell), and rules are provided for the evaluation of local metal loss at a nozzle connection. Level II assessments would typically be conducted by plant engineers, or engineering specialists experienced and knowledgeable in performing FFS assessments. The Level 2 assessment rules provide a better estimate of the structural integrity of a component when significant variations in the thickness profile occur within the region of metal loss. Hence a component that fails to be fit for service from Level I assessment can pass from a detailed Level II.

However, the Level II procedures still have some limitations regarding the component type, location of damage, loading and damage type that can be assessed. Level III Assessment The assessment procedures included in this level are intended to provide the most detailed evaluation which produces results that are more precise than those from a Level II assessment.

2.11.4. LEVEL III ASSESSMENT

In a Level III assessment, the most detailed inspection and component information is typically required, and the recommended analysis is based on numerical techniques such as the finite element method or physical testing when appropriate. Level III assessment rules are intended to evaluate components with complex geometries, regions of localized metal loss and/or components with details where only limited design rules are provided in the original construction code or standard.

A Level III assessment is primarily intended for use by engineering specialists experienced and knowledgeable in performing FFS assessments. Since advanced numerical procedures are used for stress analysis, the limitations of level 1 or level 2 procedures are surpassed in this level.

2.11.5. FITNESS FOR SERVICE PROCEDURES FOR LOCAL THIN AREAS

Damages due to corrosion/erosion in the form of blunt metal loss are a widespread problem in storage tanks. Elaborate research had been carried out to address the FFS issues due to locally thinned areas. These LTA damages can be global (over the entire area) or local (at certain locations). These damages are progressive and may or may not adversely affect the safety of the equipment at a particular instant.

Hence FFS assessments are periodically carried out to evaluate the damages and ensure the required safety and serviceability of the equipment. The fitness for service procedures for wall thinning or metal loss is generally divided in to three categories:

- General Metal Loss (GML)
- Local Metal Loss (also referred to as local thin area or LTA)

- Pitting

The objective of performing FFS assessment is to check for rupture, bulging and leakage. The procedures ensure that the corroded (or eroded) component has sufficient strength to resist applied loads and is sufficiently thick to prevent pinhole leaks. The rupture prevention is based on the concept of metal reinforcement, i.e., the weak thin metal area is reinforced by surrounding sound metal provided the thin metal area is not too large and leak prevention is ensured by keeping the remaining wall thickness above a minimum threshold. The principal failure mode for a pressure vessel (including tanks) with LTA subject to constant internal pressure is plastic collapse. Plastic collapse may be evaluated using elastic stress analysis, limit load analysis, plastic collapse analysis or using the concept of remaining strength factor. The remaining strength factor method has been adopted in API 579-1/ASME FFS-1 standard. It has proven to be effective in several applications. The method using remaining strength factor are reviewed in the following paragraphs.

2.11.6. LIMIT LOAD ANALYSIS

Limit analysis is a design philosophy used for designing mechanical components and engineering structures. The method is based on maintaining equilibrium of the structure at all stages of loading and thereby determining the safe load called the limit load just prior to plastic failure (unconstrained plastic flow) of the structure/component.

The load, that triggers overall structural instability or plastic collapse, corresponding to a point in the load-displacement curve at which the rate of external work of applied load does not balance the rate of plastic dissipation.

Limit analysis offers a more realistic and economical design than the methods based purely on elastic analysis.

The limit load can be determined using analytical methods, detailed numerical procedures or simplified methods. The analytical procedures use the bounding theorems of limit analysis, while the numerical procedures employ the widely used finite element analysis (or similar methods) to determine the limit load. The analytical procedure will not be feasible for complicated structures and is restricted to simple geometry and loading.

Hence, nonlinear FEA is a widely adopted and recognized procedure for detailed limit analysis. However, performing nonlinear FEA involves huge computing resources, time and expertise. Simplified methods derived from the basic limit theorems and vibrational plasticity concepts might be able to predict limit load using the much simpler linear FEA. Limit analysis using simplified procedures can also be used in the fitness for service procedures for pressure vessels and tanks [30].

2.11.7. THE m_α-TANGENT METHOD

Among numerous simplified procedures for estimation of limit load, the method developed by Seshadri and co-workers [31]. it is based on variational principles in plasticity and makes use of a statically admissible stress field based on linear elastic analysis. Limit load multiplier is a factor that scales the applied load proportionately to obtain the limit load. The m_α – tangent method depends on the 'reference volume' of the structure based on the magnitude of maximum stress in the structure. The reference volume is the part of the entire volume that actually participates in the plastic failure of the structure or component.

2.11.8. REMAINING STRENGTH FACTOR METHOD

API 579-1/ASME FFS-1 Metal Loss Assessment Procedure Before any standardized procedures were introduced; regions of metal loss were assessed using thickness averaging techniques. In these methods, since the flaw depth is generally irregular and varies over the entire area, it is averaged over the flaw length (or width) and a uniform depth is assumed for that length of LTA. Assessment techniques were developed by Texas Eastern Transmission Corporation and AGA Pipeline research committee in the late 1960s and later incorporated in the ASME codes as B31.G method. Though the averaging technique is not accurate for complex damage profiles, it gives the most conservative results of all the proposed methods [Janelle, 2005]. This method forms the foundation for most of the local thin area assessments that are currently in use. API Standard "Fitness for Service - API 579-1/ASME FFS-1, 2012" is a compendium of consensus methods for reliable assessment of the structural integrity of equipment containing identified flaws or damage. It provides standardized and technically sound consensus approaches. It is written as a Recommended Practice rather than as a mandatory standard or code and is to be used in conjunction with the refining and petrochemical industry's existing codes for pressure vessels, piping and aboveground storage tanks (API 510, API 570 and API653). API 579-1/ASME FFS-1 uses modified thickness averaging rules as well as specific problem based procedures. This assessment method has two main classifications namely the Local Metal Loss and Global Metal Loss. The procedure has three levels of assessment as mentioned before.

2.12. DATA REQUIREMENTS FOR CHARACTERIZING METAL LOSS

Several non-destructive techniques are available to inspect the extent of the metal loss/leakage in tanks and pressure vessels. The choice depends upon the material, type of flaw, access to surface, availability, cost, etc. Some of the inspection techniques used in the process industry are visual examination, magnetic particle testing, radiographic testing, ultrasonic testing, acoustic emission testing and thermography. Fitness for service assessments for wall thinning cannot be performed from thickness measurement at a single sample point. Usually ultrasonic thickness readings are measured in a grid with a minimum spacing equal to twice the nominal wall thickness of the vessel [32]. The region of metal loss can be characterized by two thickness measurement techniques, namely point thickness reading (PTR) and critical thickness profile (CTP). PTR is random sampling of thickness measurement that can be used only if the variation in thickness readings is statistically small. The variation in the thickness reading is expressed using Coefficient of Variation (COV), which is defined as the standard deviation of a sample divided by the mean of the sample, Mathematically:

$$COV = \text{Standard Deviation} / \text{Mean} \tag{2.6}$$

The CTP is established using thickness reading from a measurement grid with suitable interval to allow for accurate characterization of the metal loss. For most of the pressure vessels and pipe lines, the CTP should be established in both the meridional (longitudinal) and circumferential directions following the geometry profile. Figure 2-11 give an example of the for measuring the thickness through a segment of the floor area, which in terms applied for the whole tank floor area. Furthermore, for atmospheric tanks, only the CTP along the meridional direction is required by the standard and hence the meridional inspection planes are sufficient. The circumferential inspection planes are not required because the stress in the direction normal to the hoop is considered negligible and does not govern the design thickness calculation [28] [29].

After obtaining the thickness readings of individual locations in the grid, the CTP in the meridional direction is established by projecting the minimum thickness point at each interval along the inspection planes on to a common plane.

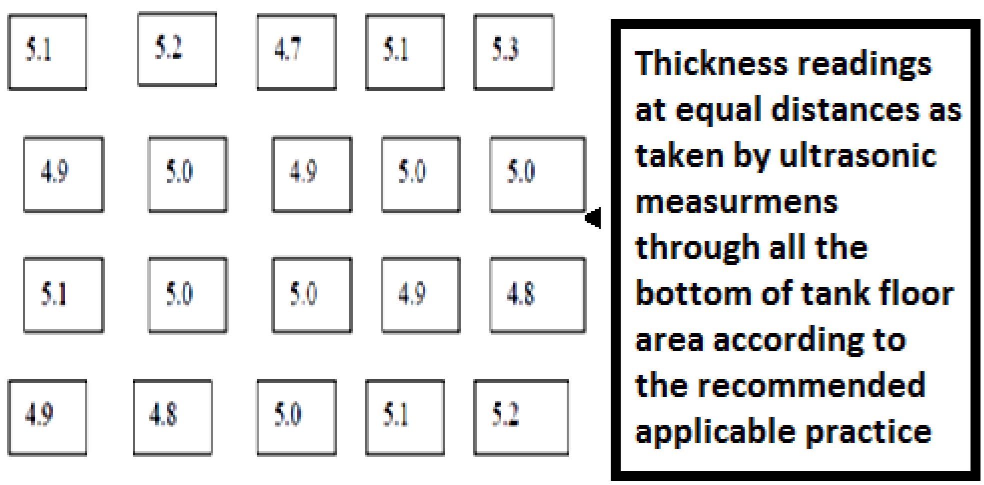


Figure 2-11: The procedure for measuring the thickness through all the floor area.

The detailed procedure to establish the CTP is given in API 579-1/ASME FFS-1 Cl.4.3.3.3 in which t_c represents uniform thickness (after general metal loss resulting from corrosion, erosion, or both) away from the local metal loss, to be used in FFS assessment procedures and t_{mm} represents minimum measured wall thickness in the LTA. Thus the sequencing of the evaluation of FFS through CTP may be conducted by determining the data required for the procedure below:

(a) Inspection Planes and the Critical Thickness Profile

(b) Critical Thickness Profile (CTP) - Longitudinal Plane (Projection of Line) [API 579-1/ASME FFS-1] After establishing the CTP, FFS procedures are used for three different levels of assessment.

2.12.1 RESEARCH OF FITNESS FOR SERVICE FOR LOCAL THIN AREA

Determination of fitness for service condition of damaged equipment is not yet an exact science [33].Researchers have continuously improved the safety and reliability of the FFS procedures using full scale burst tests, finite element analysis and statistical methods. The following is a brief list of research by various authors.

Folias, [34] [35],formulated detailed analytical expression to correlate stress field in flat and curved plates with finite crack. He extended the study and proposed analytical expressions to determine the state of stress near the crack tip in a spherical/cylindrical shell. Modified versions of the expression proposed by him are now widely used as “Folias factor” or “Folias bulging factor” in many fitness for service procedures involving LTA or crack like flaw. His theory is probably the most influential of the many available ideas.

Chen, et al. [36],proposed an empirical formula for obtaining the load carrying capacity of pressure vessels with two part-through defects. The article discusses the effects of the distance between the two defects on the load carrying capacity of pressure vessels. The authors conclude that their numerical results confirm the applicability of the simplified numerical method.

Konusu [37],proposed an assessment procedure for multiple volumetric flaws (locally thin areas). He comments that in the current practice as prescribed in ASME BPVC, BS 7910, API 579 and similar standards, multiple flaws are characterized as a single larger flaw enveloping the individual smaller flaws, which may provide unrealistic assessment in some cases. Hence a new assessment procedure is proposed in this article, which is based on the interaction between differently sized flaws. American Petroleum Institute's Standard - API 650 is the premier standard for tank design in many parts of the world amongst which Sudan. The standard establishes minimum requirements for material, design, fabrication, erection, and testing for vertical, cylindrical, aboveground, closed and open-top, welded storage tanks in various sizes and capacities for internal pressures approximating atmospheric pressure. This standard applies only to tanks whose entire bottom is uniformly supported and to tanks in non-refrigerated service that have a maximum design temperature of 93C° (200 F) or less. This standard provides procedures for design of tank shell (wall), annular plate, bottom plate, roof, nozzles, stiffeners, wind girders etc., Most of the work in the current thesis is depend for verifications and referencing upon the evaluation and design procedures of this standards scopes.

API 653 Standard “Tank Inspection, Repair, Alteration and Reconstruction [29] ,is a post construction standard that provides the minimum requirements for maintaining the integrity of tanks after they have been placed in service and addresses inspection, repair, alteration, relocation, and reconstruction issues. This standard covers steel storage tanks built in accordance to API 650 (or its predecessor API 12C). It recognizes fitness-for-service assessment concepts for evaluating in-service degradation of tanks in a limited way. But API 579-1/ASME FFS-1, Fitness-For-Service standard, provides detailed assessment procedures or acceptance criteria for specific types of degradation referenced in API 653 standard. When API 653 standard does not provide specific evaluation procedures or acceptance criteria for a particular type of degradation, API 579-1/ASME FFS-1 may be used to supplement or augment the FFS requirements in API 653.For assessment of single LTA flaws, the BS 7910 provides general guidelines to assess remaining strength factor (similar to Residual Strength Factor of API) based on the work by Batte, et al., [38]and Fu and Kirkwood [39].The remaining strength factor is determined based on the strength of the remaining ligament in the LTA portion to prevent plastic collapse due to bulging.

Since the guidelines provided are not exhaustive, it refers to the work by Sims, et al., [40] for further details. It should be noted that Sims was responsible for developing the RSF acceptability criterion adopted in API 579 as well. The literature review about FFS procedures given in this section gives the global picture of the research carried out in developing the general procedure for determination of RSF in corroded tanks. The publications reviewed and presented here give an overall idea about the up-to-date background of the development of general FFS methods.

2.13. SUMMARY

The basic theories of mechanics pertaining to the area of this research work are briefly presented. The current thesis aims to re-evaluate and improve specific design aspects researched mainly the widely used standard API 650, 653 and API recommended practice 579-1/ASME. The fitness for service of pressure vessels and pipelines is a well-researched area for past several decades. Most of the assessment procedures till now are empirical in nature and hence there is a continuous attempt to improve the accuracy of these models. FFS I and FFS II still has several limitations in its methods regarding the applicability to the type of component, damage, location, and loading conditions. Using FEA and simplified limit load procedures for Level II FFS procedures is a recent trending development in this area. From which is the scope of this work to study with aid of FEA tools the FFS assessment to made improvements in storage tanks with corroded bottom plates.

CHAPTER THREE

METHODOLOGY

3.1. PREFACE

This chapter introduces the basic tank design procedures and mapping the bottom plate and its design basis. the procedure for vacuum and ultra-sonic tests and results are explained. the influence of the plate thickness on tank stresses is studied.

The following chart give hierarchy for the sequencing of the procedure followed to conduct this search where two tests are carried out , namely Vacuum box test and Ultrasonic test , the purpose of the vacuum test for the bottom plates and the first and second shell courses was to verify that the plate is free of punching or cracks that when present give an evidence that the defected positions should be replaced especially that that tank is not equipped with a leak detection system, since no defect found this enable to carry out the Ultrasonic test for the measurements of thickness of the tank plates.

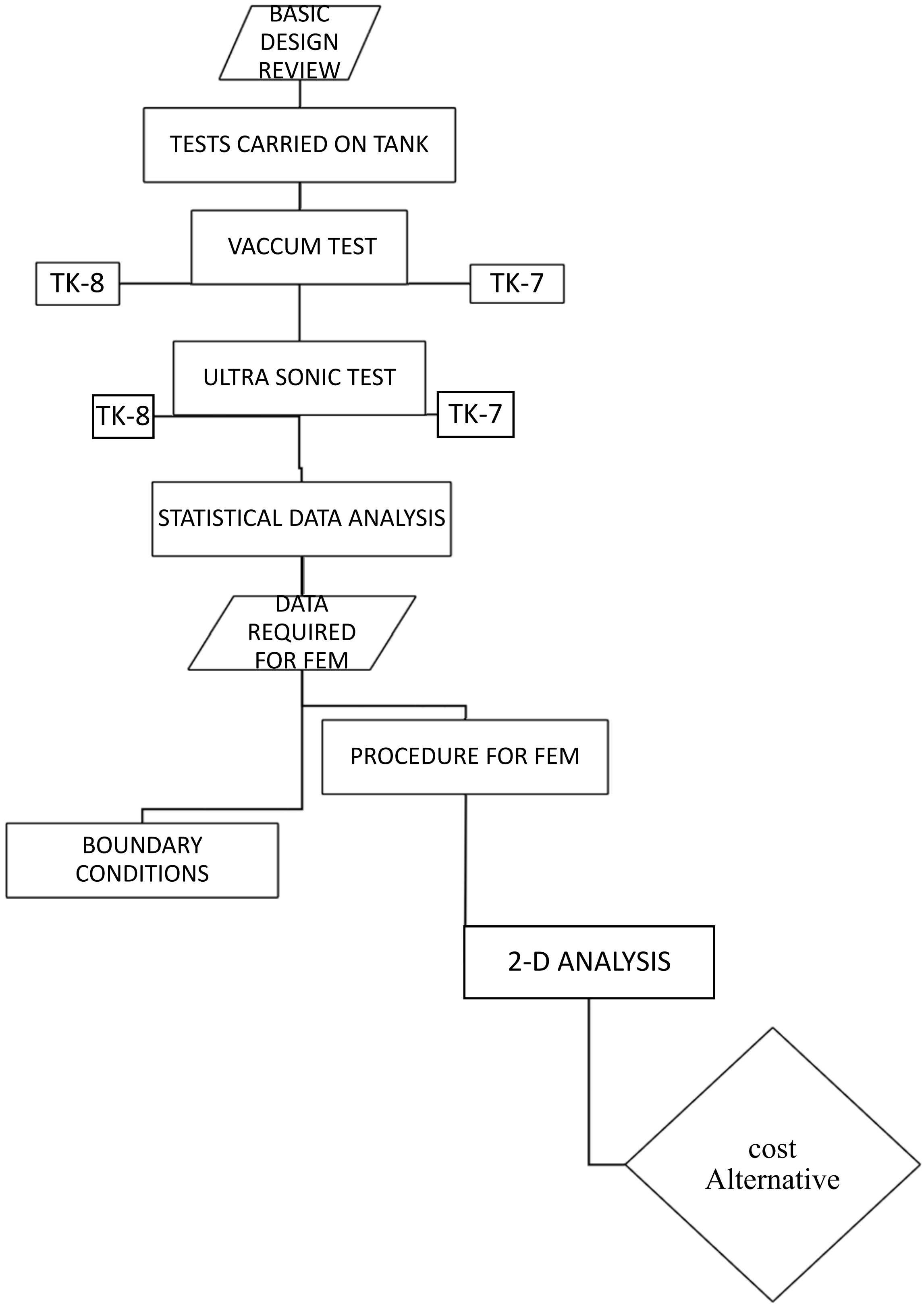


Figure 3-1: Operational framework of the methodology

3.2. VACCUM TEST

The objective of the vacuum box technique of bubble leak testing is to locate leaks in a pressure boundary that cannot be directly pressurized. This is accomplished by applying a solution to a local area of the pressure boundary surface and creating a differential pressure across that local area of the boundary causing the formation of bubbles as leakage gas passes through the solution.

The purpose of this procedure is provide a guide line to carry out the Vacuum box test to check soundness of annular joints, bottom (long seam & short seam) and welding joints for annular plates. The test conducted as per reference codes:

1. API-650 cl. 7.3.4 & 8.6 11^{th} edition
2. ASME Sec-V

The Vacuum box test is performed by using a box with visible window of fiber glass (i.e. 15.24 cm Width by 76.2 cm length metallic box). The open bottom is sealed against the tank surface by a sponge rubber gasket. The test scheme has suitable connections, necessary valve and calibrated Vacuum gauge.

The gauge registers a reading of partial Vacuum of 21 KPa for inspection of the joints. An Overlap of 5 cm minimum for adjacent placement of the Vacuum box is given for each subsequent examination.

The required partial vacuum was maintained for at least for 10 seconds examination time stop watch was used after reaching the 21 KPa / Designated vacuum.

Bubbles produced by air sucked through the welded seam can detect the presence of defect. The tested areas are accepted since no continuous bubbles formation is observed.

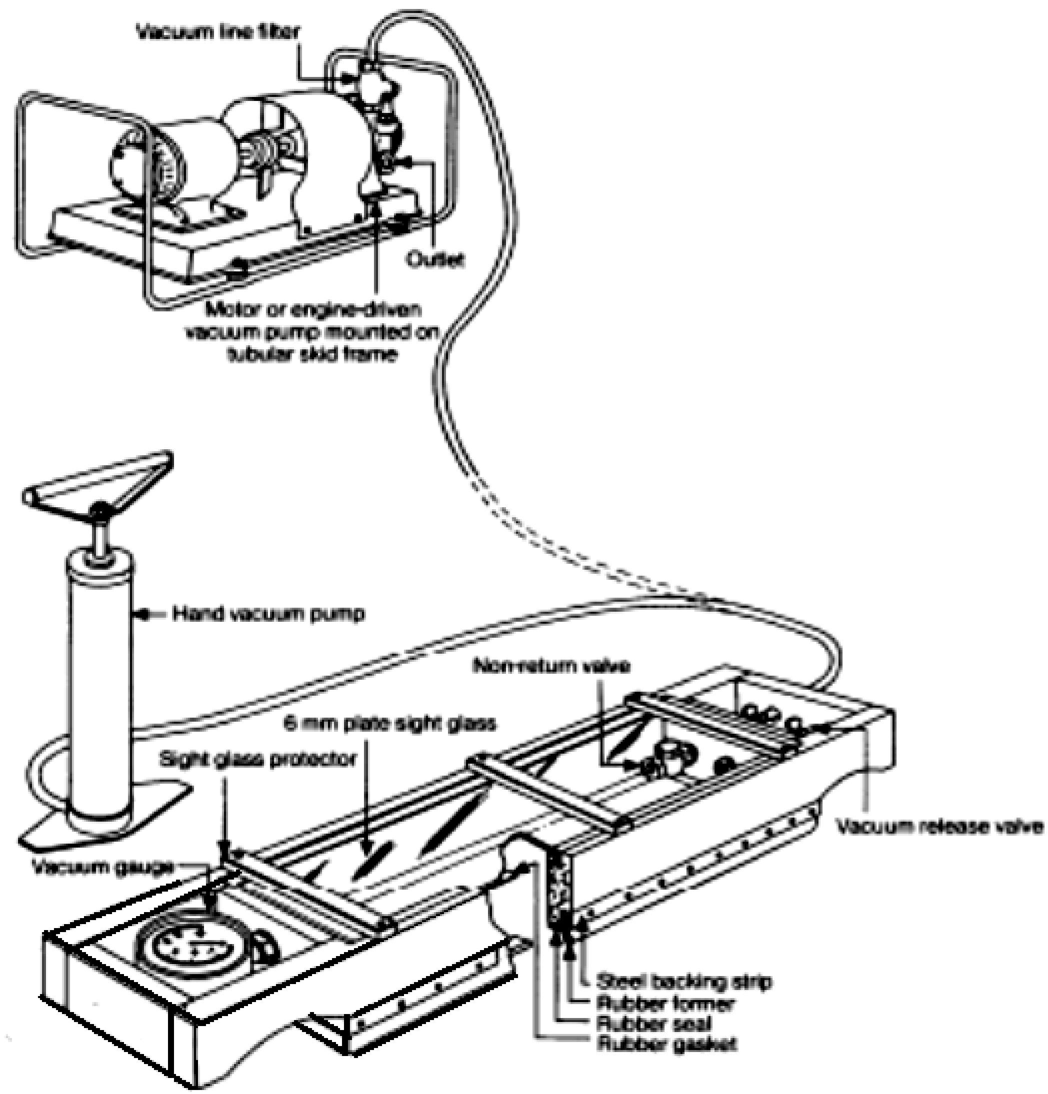


Figure 3-2: Typical motor driven Vacuum Test Equipment.

3.3. ULTRASONIC TEST

Ultrasonic test is a non-destructive technique that followed to inspect the extent of the metal loss/leakage in tanks and pressure vessels.

Ultrasonic thickness readings are measured in a grid with a minimum spacing equal to twice the nominal wall thickness of the measured area. The region of metal loss can be characterized by two thickness measurement techniques, namely point thickness reading (PTR) and critical thickness profile (CTP). PTR is random sampling of thickness measurement that can be used only if the variation in thickness readings is statistically small.

Ultrasonic testing to be effective, requires a high degree of operator skill, accurate calibration of the ultrasonic machine is essential for detection, location and sizing of thickness, the following simplified example give an overview of how the thickness determined considering the equation:

$$\mathbf{V} = \mathbf{l} \times \mathbf{f} \quad \mathbf{(3.1)}$$

Where,

V = velocity, m/sec

l = Wavelength, m

f = Frequency, Hz (unit of frequency is the Hertz which is the number of cycles per second and has the dimensions' sec^{-1})

then, a typical ultrasonic wave in steel:

Steel V = 5.85×10^3 m/sec.

Frequency f = 2.25 MHZ (2,250,000 cycles/sec)

Wavelength l = V / f

$= (5.85 \times 10^3)/(2.25 \times 106)$

$= 2.6 \times 10^{-3}m = 2.6$ mm

Thus the thickness of the measured segment will be 2.6 mm.

3.3.1. Piezoelectric transducers

The conversion of electric pulses to mechanical vibrations and the conversion of returned mechanical vibration back into electrical energy is the basis for the ultrasonic testing. this conversion is done by the transducer using a piece of piezoelectric martial which is a polarized material having some parts of the molecules positively charged while other parts of the molecules are negatively charged, with electrodes attached to two of its opposite faces. When an electric field is applied across the material, the polarized molecules will align themselves with the electric field causing the material to change dimensions. In addition, a permanently polarized material such as quartz (Sio_3) or barium titanate ($BaTiO_3$) will produce an electric field when the material changes dimensions as a result of an imposed mechanical force. this phenomenon is known as piezoelectric effect.

The active element used for the acoustic transducer is a piezoelectric ceramic, that could be cut into various ways to produce different wave modes. The thickness of the active element is determined by the desired frequency of the transducer. A thin wafer element vibrates with a wave length that is twice its thickness, therefore the piezoelectric crystals cut to thickness that is half of the desired radiated wavelength, the higher the frequency of the transducer, the thinner the active element is. Many factors including material, mechanical and electrical construction, and the external mechanical and electrical load conditions, are all influence the behavior of a transducer. Figure 3-3 shows a cut away of a typical contact transducer.

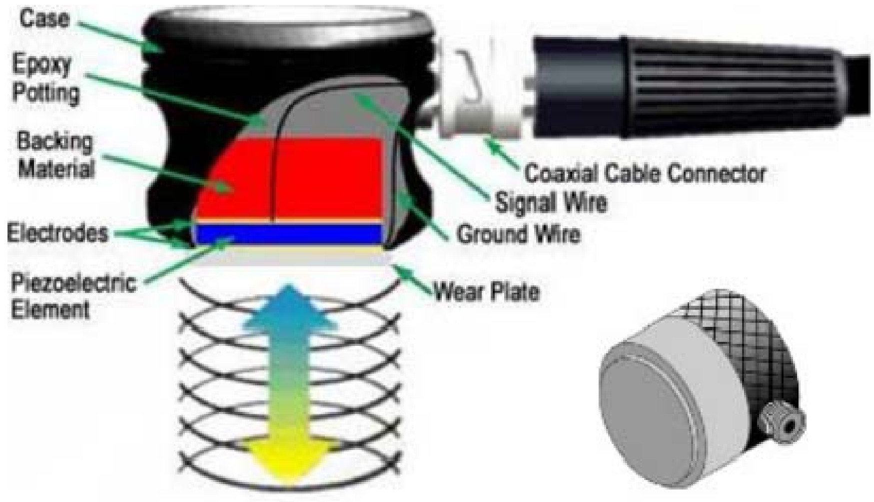


Figure 3-3: cut away of typical contact transducer element.

3.3.1. EVALUATION

The variation in the thickness reading is expressed using Coefficient of Variation (COV), which is defined as the standard deviation of a sample divided by the mean of the sample. recalling equation (2.6):

$$\text{COV}=\frac{\text{standard deviation}}{\text{mean of the sample}} \tag{2.6}$$

If the COV of the thickness reading population minus the Future Corrosion Allowance (FCA) if applied is less than 10 %, then the metal loss can be considered as uniform over the area and hence the average thickness value calculated directly from the population can be used for FFS calculations.

3.4. FINITE ELEMENT MODEL

2-D Model drafted by ANSYS in 2-D environment to represent the tank geometry with a full definition of forces acting on bottom and shell of the tank in addition to the consideration of the bottom to be fixed from the underneath since it actually anchored to the concrete ring base with a countersunk bolts.

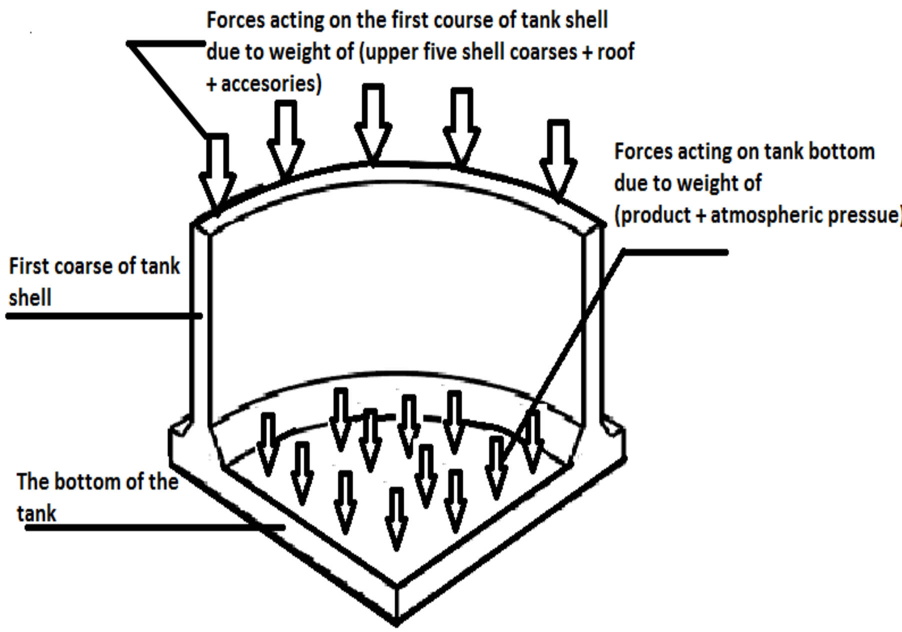


Figure 3-4: Quarter segment illustrates the distribution of force on the shell and the bottom plates.

3.4.1. SIMULATION PROCEDURE

After Opening Static Structural at ANSYS Software interface. As the software window shown in figure 3-5, all sub categories to conduct the simulation Engineering Data, Geometry, Model, Setup, Solution and, Result as illustrated in step by step procedure with the following figures. Where the value of the parameters definition to software to represent the working environment are sorted in table 3-1.

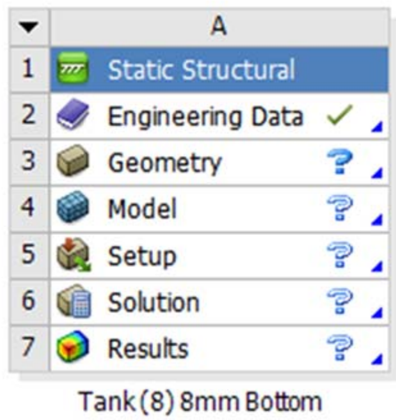


Figure 3-5: The main interface for ANSYS Static Structural

Table 3-1: The parameters used for the bottom calculation check and for simulation.

Nominal diameter of tank, D			24,380	Mm
Total height of tank shell, *Ht*			12,000	Mm
Maximum design liquid level, *H*			12,000	Mm
Design specific gravity of liquid, *G*			1	
Total weight of tank shell, *Ws*		59,456 kg	583,273	N
Total weight of tank roof, *Wr*		5,260 kg	51,596	N
Total weight of tank contents, *Wp*		5,601,941 kg	54,955,041	N
Total weight of tank bottom, *Wf*				
Case 1	Thickness = 8 mm	29,115 kg	285,621	**N**
Case 2	Thickness = 5.091 mm	20,822 kg	204,264	**N**
Case3	Thickness = 4.123 mm	16,740 kg	164,212	**N**
Case 4	Thickness = 2.7 mm	11,024 kg	99,211	**N**
Case 5	Thickness = 1.7 mm	6,941 kg	68,088	N

Engineering Data Tap is used to define the properties for the materials that will be used in experiment selected from ANSYS Software Library, as in figure 3-6 it could be created, described and could be added to ANSYS library.

Properties of Outline Row 3: AL2O3 CERA

	A	B	C	D	E
1	Property	Value	Unit		
2	Density	3900	kg m^-3		
3	Bilinear Isotropic Hardening				
4	Yield Strength	8E+09	Pa		
5	Tangent Modulus	0	Pa		
6	Shear Modulus	1E+11	Pa		
7	Shock EOS Linear				
8	Gruneisen Coefficient	0.5			
9	Parameter C1	6900	m s^-1		

Figure 3-6: Engineering Data for Material properties.

From Geometry tap 2D model created, ANSYS is capable to create sketches with a simplified sketching tools figure 3-7 shows steps for model sketching In Model tap Assign Material for models (structural steel ASTM A36) for tank material.

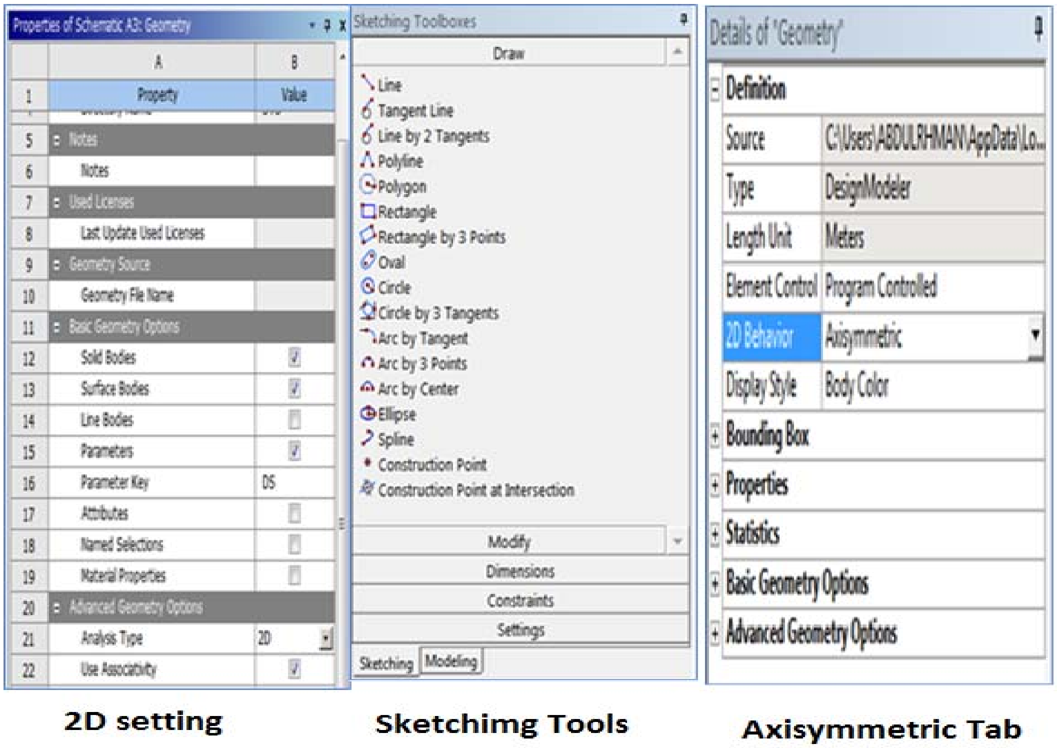
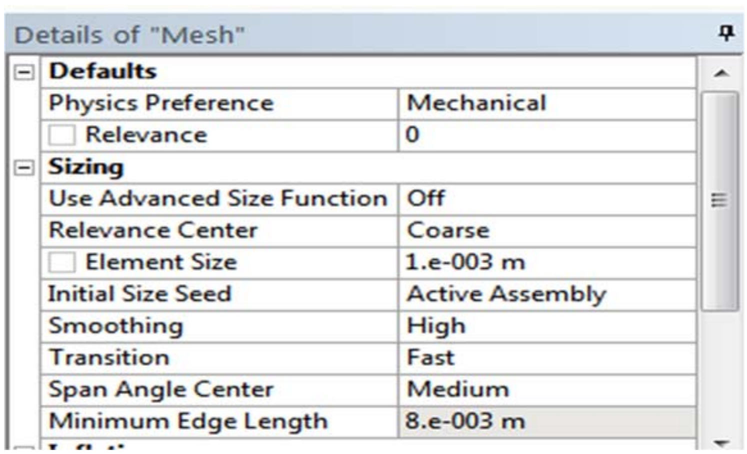


Figure 3-7: Sketching tools for the 2D model generation.

Mesh Sizing when setting size for mesh, as in figure 3-8, the smaller the size division, the test accuracy increased but the time required of processing the analysis will be greatly extended and the data space (storage) will be in Gigabytes rather than Megabytes for less mesh size. In this research mesh size set to 0.001m.


Details of "Mesh"

Defaults	
Physics Preference	Mechanical
Relevance	0
Sizing	
Use Advanced Size Function	Off
Relevance Center	Coarse
Element Size	1.e-003 m
Initial Size Seed	Active Assembly
Smoothing	High
Transition	Fast
Span Angle Center	Medium
Minimum Edge Length	8.e-003 m

Figure 3-8: The sizing of mesh.

In Analysis settings forces converted to pressure acting on the effective area of bottom and on the top of the area of the first shell coarse equals to 0.741 MPa which is the sum of weight of the upper five coarse plus the roof and appliances acting on the top of the first shell coarse and equals to 0.118(of liquid) + 0.1013atm=0.2193 MPa, figure 3-9 shows the window for the details of pressure as defined to the program interface. Then, fixed support defined at the lower side of the tank model. Finally, in **Results** tap solving methods Determent which is (Equivalent Von Mises stress) and showing the stress distribution and the form of deformation through all the tank floor zoom and first lower shell coarse, this illustrated in figure 3-10 which outline the type of results that could be shown according to the initial data input and the type of the analysis conducted.

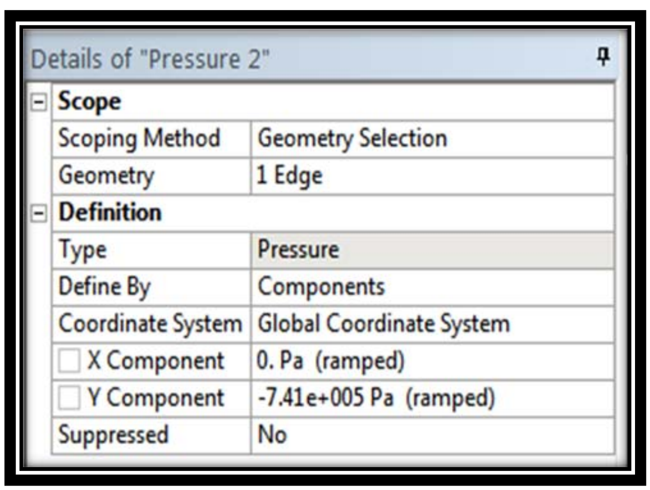


Figure 3-9: The equivalent magnitude of (force)pressure applied on top surface of first shell coarse.

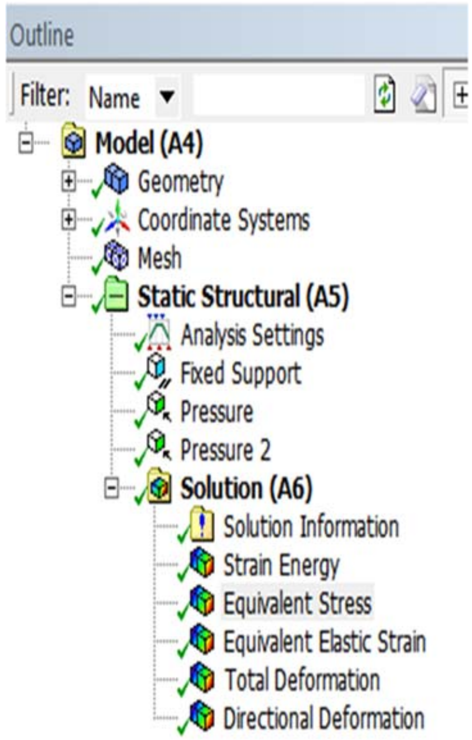


Figure 3-10: The solution screen presenting the solution information's.

CHAPTER FOUR

RESULTS AND DISCUSSION

4.1. PREFACE

In this chapter the results of the analysis made of the bottom of tank 8 which abbreviated as TK-8 and relatively results of tank 7 TK-7 are considered for comparison, the results shown include:

- Design review and consideration
- Thickness reading results.
- Data, analysis and comparison of statistical parameters of bottom thickness.
- Corrosion rate determination. And,
- Finite Element Results.

4.2. DESIGN REVIEW AND CONSIDERATION FOR TK-8

The Nominal capacity of the tank in Basic design is 5.1 million liters, to this end, given the constraint in the existing tank of diameter 24.38m and height 12.5m was considered. The following design review was carried out in consonance with the requirements of the API 650 [2].

The tank capacity was calculated using the formula:

$$\mathbf{C = 0.785D^2H} \tag{4.1}$$

Where:

C *=Capacity of the tank in m3*

D *= Diameter of tank in m*

H *= Height of tank in m*

$$C = 0.785x\ (24.38)^2 x\ 12.0 = 5{,}599{,}101 \text{ liters}$$

Section 5.6.3.1 of the API 650 recommends the use of one-foot method for calculating shell thickness for tanks of diameters less than 61m, therefore this technique was adopted rather than the variable design-point method.

4.2.1. TANK SHELL DESIGN

According to API 650 section 5.6.3.2 the minimum required thickness of shell plates shall be the greater of the values computed by the following formulas:

$$t_d = \frac{4.9D(H-0.3)G}{S_d} + CA \qquad (4.2)$$

and,

$$t_t = \frac{4.9D(H-0.3)G}{S_t} \qquad (4.3)$$

Where:

t_d = *design shell thickness, in mm,*

t_t = *hydrostatic test shell thickness, in mm,*

D = *nominal tank diameter, in m =24.38m,*

H = *design liquid level, in m = 12m,*

G = *design specific gravity of the liquid to be stored, =0.85 for Diesel and 1.00 for Water*

CA = *corrosion allowance, in mm .*

S_d = *allowable stress for the design condition, =160 MPa for ASTM A 36 Carbon steel as in table (4.1),and ,*

S_t = *allowable stress for the hydrostatic test condition, =171 MPa for ASTM A 36 Carbon steel as in table (4.1).*

Jumbo plates of dimension width 2.0m and length 10m were selected as this means less joint to be welded and hence most economical. With the jumbo plate of width 2.00m and tank height of 12.00m, the number of shell courses will be: 12.0÷ 2.0 = 6 courses.

Table 4-1: Allowable plate materials and allowable stresses , Source [2].

Plate Specification	Grade	Nominal Plate Thickness t mm	Minimum Yield Strength Mpa	Minimum Tensile Strength Mpa	Product Design Stress S_d Mpa	Hydrostatic Test Stress S_t Mpa
ASTM Specifications						
A 283M	C		205	380	137	154
A 285M	C		205	380	137	154
A 131M	A, B		235	400	157	171
A 36M	—		250	400	160	171

As it necessary to provide a specific data required for the design of the type of tank that suit the predetermined specific purposes of the tank in addition to matching the standards, codes and the recommended practices table (4.2) below give an executive summary of the data upon which the design of TK-8 was made.

4.2.2. SHELL THICKNESS CHECK

To verify that every separate coarse thickness of the shell is adequate enough to withstand and work safely under the different loading conditions a comparison made between design shell thickness t_d ,and the hydrostatic test shell thickness t_t using equations (4.2) and, (4.3) taking that the thickness is considered adequate when the value of the design thickness become greater than that of the hydrostatic test, table 4-3 summarizes the comparison results for the six coarses of the shell.

Table 4-2: Basic Tank Data summary.

Description	Unit	Values
Diameter, D	m	24.38
Total Tank Height of Shell, H1	m	12
Maximum Design Liquid Level, H2	m	12
Nominal Capacity, Q1	m^3	5599
Gross Capacity, Q2	m^3	5000
Effective Capacity, Q3	m^3	4750
Specific Gravity of LDO , G	-	0.85
Design Density of liquid, ρ	kg/m^3	1000
Design Pressure, P	mLC	Hydrostatic Head
Vacuum Pressure, Vp	kg/m^2	63.5
Design Temperature, T	°C	60
Corrosion Allowance , C	mm	N/A
Joint Efficiency Factor, E	-	1
Non-destructive Examination	Ultra-Sonic Test	
Material of Construction	Steel A-36	
Width of Shell Plates, W_s	m	2
Width of Bottom Plates, W_b	m	1.5
Width of Roof Plates, W_r	m	2

Table 4-3: Tank shell thickness Comparison using t_d against t_t.

Course No.	H (m)	t_d (mm)	t_s (mm)	Comparison using design thickness as basis (t_d VS t_t)
1st	12	8.74	8.17	$t_d > t_t$,12mm plate is accepted
2nd	10	7.24	6.78	$t_d > t_t$ 10mm plate is accepted
3rd	8	5.75	5.38	$t_d > t_t$ 10mm plate is accepted
4th	6	4.26	3.98	$t_d > t_t$ 8mm plate is accepted
5th	4	2.76	2.58	$t_d > t_t$ 8mm plate is accepted
6th	2	1.27	1.19	$t_d > t_t$ 8mm plate is accepted

4.2.3. BOTTOM PLATE SIZING

According to API section 5.4.1, the minimum thickness of the bottom plate should be 6mm. From experience therefore, 8mm plates was originally selected. The bottom plates development is presented in Figure 4-1.

Bottom Plate is assumed to be simply supported rectangular plate under uniform pressure; The bottom plate has been provided with stiffeners at a span of 666 mm X 375 mm i.e. $b_1 = 0.666$m & $a_1 = 0.375$m. (a & b values as per geometry requirement). Therefore, $b_1 / a_1 = 0.666/ 0.375 = 1.7$

Now, as per Table 6, of TPS(Theory of Plates) [24]:

$$\mathbf{M_x = \beta' q_1 a_1^2} \qquad (4.5)$$

And;

$$\mathbf{M_y = \beta'_1 q_1 a_1^2} \qquad (4.6)$$

where,

$\mathbf{M_x}$ = *Bending moment about 'X-axis'*

$\mathbf{M_y}$ = *Bending moment about 'Y-axis'*

$\mathbf{q_1}$ = *(Hydrostatic Pressure + Unit weight of Plate) in kg/cm²*

= Pressure due to water column of 12000 mm + Weight of plate / Plate area

= [0.20 + 3000X2000x8x0.00000785/(300x200)] (considering 8mm thickness Plate)

$= 1.19 + 0.00628$

$= 1.19628 \text{ kg/cm}^2$

$= 0.117315 \text{ MPa}$

$\beta' = 0.0555$(interpolated from Table) [24].

$\beta'_1 = 0.0493$ (interpolated from Table) [24].

Therefore, putting the values in eqns. (4.5) & (4.6), we get

$M_x = 0.0555 \text{ x } 1.19628 \text{ x } (37.5)^2$

$=93.395$ kg-cm

and,

$M_y = 0.0493 \text{ x } 0.20628 \text{ x } (37.5)^2$

$= 82.935$ kg-cm

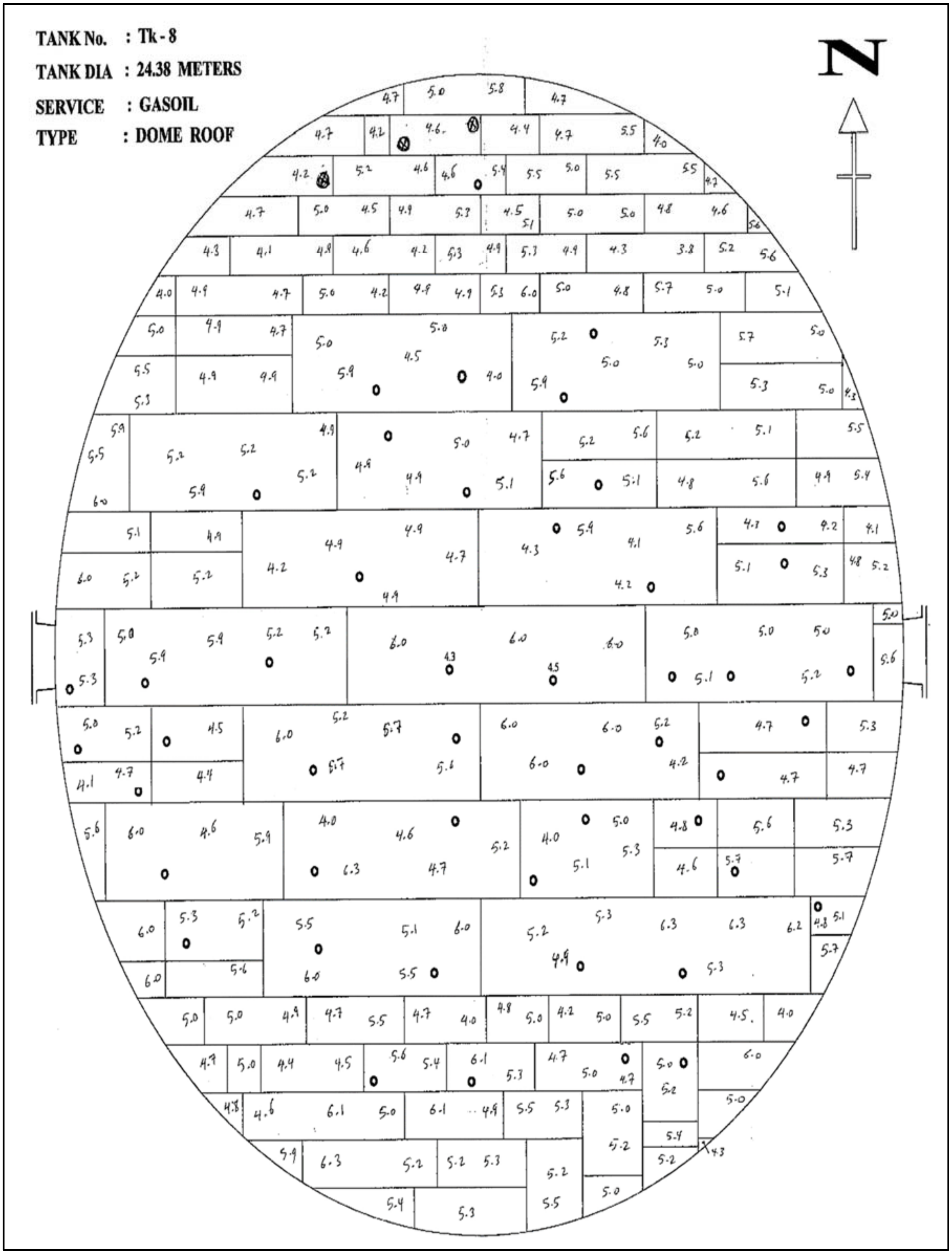


Figure 4-1: Bottom plates wall thickness map (the ultrasonic resuls).

Thus Resultant Bending Moment, M_1 =

$$= \sqrt{(M_x^2 + M_y^2)} \quad (4.7)$$

$$= \sqrt{(16.09^2 + 14.3^2)}$$

$$= 124.9 \text{ kg-cm}$$

Table 4-4: Values of β' and β'1 for determining the Bending moment about 'X-axis' and 'Y-axis'.

b/a	$M_x = \beta' q a^2, y = 0$					$M_y = \beta_1' q a^2, y = 0$				
	$x = 0.1a$	$x = 0.2a$	$x = 0.3a$	$x = 0.4a$	$x = 0.5a$	$x = 0.1a$	$x = 0.2a$	$x = 0.3a$	$x = 0.4a$	$x = 0.5a$
1.0	0.0209	0.0343	0.0424	0.0466	0.0479	0.0168	0.0303	0.0400	0.0459	0.0479
1.1	0.0234	0.0389	0.0486	0.0541	0.0554	0.0172	0.0311	0.0412	0.0475	0.0493
1.2	0.0256	0.0432	0.0545	0.0607	0.0627	0.0174	0.0315	0.0417	0.0480	0.0501
1.3	0.0277	0.0472	0.0599	0.0671	0.0694	0.0175	0.0316	0.0419	0.0482	0.0503
1.4	0.0297	0.0509	0.0649	0.0730	0.0755	0.0175	0.0315	0.0418	0.0481	0.0502
1.5	0.0314	0.0544	0.0695	0.0783	0.0812	0.0173	0.0312	0.0415	0.0478	0.0498
1.6	0.0330	0.0572	0.0736	0.0831	0.0862	0.0171	0.0309	0.0411	0.0472	0.0492
1.7	0.0344	0.0599	0.0773	0.0874	0.0908	0.0169	0.0306	0.0405	0.0466	0.0486
1.8	0.0357	0.0623	0.0806	0.0913	0.0948	0.0167	0.0301	0.0399	0.0459	0.0479
1.9	0.0368	0.0644	0.0835	0.0948	0.0985	0.0165	0.0297	0.0393	0.0451	0.0471
2.0	0.0378	0.0663	0.0861	0.0978	0.1017	0.0162	0.0292	0.0387	0.0444	0.0464
2.5	0.0413	0.0729	0.0952	0.1085	0.1129	0.0152	0.0272	0.0359	0.0412	0.0430
3.0	0.0431	0.0763	0.1000	0.1142	0.1189	0.0145	0.0258	0.0340	0.0390	0.0406
4.0	0.0445	0.0791	0.1038	0.1185	0.1235	0.0138	0.0246	0.0322	0.0369	0.0384
∞	0.0450	0.0800	0.1050	0.1200	0.1250	0.0135	0.0240	0.0315	0.0360	0.0375

Thus the Section Modulus Z,

$$\mathbf{Z_1} = \frac{b^4 * d^2}{6} = \frac{M}{S_d} \tag{4.8}$$

Where,

b_4 = *1 cm (Considering unit width of plate)*

d = *'t_1' in cm. (i.e. thickness of plate to be obtained)*

S_d = *Maximum Allowable Design Stress in kg/cm^2 = 152 MPa*

$= 152 \text{ X } 10.19716/\text{cm}^2$

$M = M_1 = 124.9$ kg-cm

putting the values in eqn. (4.8), we get

$$\frac{1 \text{ x } t_1^2}{6} = \frac{124.9}{152 \text{ X } 10.19716}$$

$t_1 = \sqrt{[124.9 * 6/(1560.16)]} = 0.693$ cm = 6.93 mm

Hence, Thickness of Bottom Plate provided as **8.0** mm.

4.2.4. STIFFENER SIZING FOR BOTTOM PLATE

Total load on bottom plate, W_1 = Total weight of water filled tank = 12376.8 kg = 0.206 kg/cm^2

Considering, Section of stiffener as 75 with unit weight of 6.8 kg/m

Now, as per table II, [41];

Now, uniform load on stiffener section,

$$\mathbf{w_1 = W_1 x a_1 + unit\ wt.\ Of\ section} \qquad \mathbf{(4.9)}$$

$$= 0.206*0.375*100 + 0.068 = 7.793 \text{ kg/cm}$$

Maximum length of the stiffened section, $l_1 = b_1 = 0.666\text{m} = 66.6$ cm

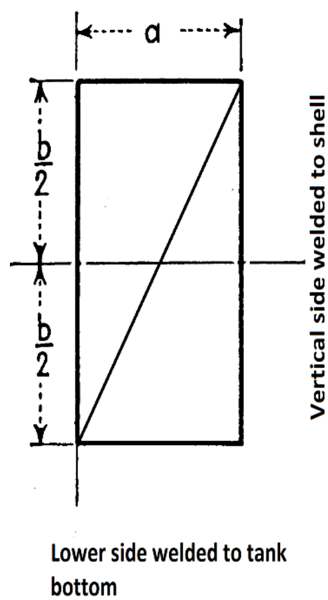


Figure 4-2: Dimensions for stiffener.

Therefore, Considering UDL on simply supported Beam; Bending Moment on stiffener section,

$$\mathbf{M_1 = wl^2/8} \qquad \mathbf{(4.10)}$$

$$= w_1 * l_1^2/8 = 7.793*66.6^2/8 = \text{ kg-cm}$$

Now, Allowable Bending Stress, σ_{bc} = 152 MPa

$= 152 * 10.19716$ kg/cm^2

Required section modulus,

$$\mathbf{Z_1 = M_1 / \sigma_{bc}} \quad \textbf{(4.11)}$$

$$= \frac{4320.78}{152 \times 10.19716} = 2.787 \text{ cm}^3$$

But, Section modulus of 75 = 20.27cm^3 > 2.787 cm^3 and thus satisfactory.

Hence, Actual Stiffener Size selected as 75.

4.2.5. DEFLECTION CALCULATION OF BOTTOM PLATE

Determination of deflection is essential to assure the integrity of the plate considering the limiting vertical deflection this could be determined as following:

$$\mathbf{W1_{max}} = \boldsymbol{\delta_{max}} = \frac{\boldsymbol{\propto * \, q * \, a^4}}{\boldsymbol{D}} = \frac{\boldsymbol{\propto * q * a^4}}{\boldsymbol{E * I}} \quad \textbf{(4.12)}$$

Where,

$W1_{max}$ = *Maximum deflection of plate in cm*

q = *Uniformly distributed load, kg/cm^2 /cm width of plate = q_1 = 2.369 kg/cm*

a = *Smaller Side of the stiffened area in cm = a_1 = 0.375 m = 37.5 cm*

D = *Flexural rigidity of the plate = EI*

α = *Numerical factor depending upon ratio b/a*

E = *Young's modulus in* $kg/cm^2 = 2x10^6\ kg/cm^2$

I = *Moment of inertia in* $cm^4 = (1/12) \times bd^3$

$= (1/12) \times 1 \times 0.8^3\ cm^4$

Considering plate width, b = 1 cm and the plate depth , d = 0.8 cm

Now,

$a = a_1$ = 0.375 m = 37.5 cm; $b = b_1$ = 0.666m = 66.6 cm

For b/a = 66.6/37.5 = 2, α = 0.00486   as per Table (4.5)

Therefore, putting the values in eqn. (4.12), we get

$$W1_{max} = \delta_{max} = \frac{0.00486 * 2.369 * (37.5)^4}{2 * 10^6 * \frac{1}{12} * 37.5 * 0.8^3} = 0.0074cm = 0.074mm$$

Now, Limiting vertical deflection, $\delta_1 = a_1/325$

= 37.5/325 = 0.1154 cm. = 1.154 mm

Since, δ_{max} *or* $W1_{max}$ is less than δ_1 , the 8.0 mm thick. bottom plate is safe under deflection.

Table 4-5: Numerical factors depending upon ratio b/a

b/a	$w_{max} = \alpha \frac{qa^4}{D}$	$(M_x)_{max} = \beta qa^2$	$(M_y)_{max} = \beta_1 qa^2$	$(Q_x)_{max} = \gamma qa$	$(Q_y)_{max} = \gamma_1 qa$	$(V_x)_{max} = \delta qa$	$(V_y)_{max} = \delta_1 qa$	$R = nqa^2$
	α	β	β_1	γ	γ_1	δ	δ_1	n
1.0	0.00406	0.0479	0.0479	0.338	0.338	0.420	0.420	0.065
1.1	0.00485	0.0554	0.0493	0.360	0.347	0.440	0.440	0.070
1.2	0.00564	0.0627	0.0501	0.380	0.353	0.455	0.453	0.074
1.3	0.00638	0.0694	0.0503	0.397	0.357	0.468	0.464	0.079
1.4	0.00705	0.0755	0.0502	0.411	0.361	0.478	0.471	0.083
1.5	0.00772	0.0812	0.0498	0.424	0.363	0.486	0.480	0.085
1.6	0.00830	0.0862	0.0492	0.435	0.365	0.491	0.485	0.086
1.7	0.00883	0.0908	0.0486	0.444	0.367	0.496	0.488	0.088
1.8	0.00931	0.0948	0.0479	0.452	0.368	0.499	0.491	0.090
1.9	0.00974	0.0985	0.0471	0.459	0.369	0.502	0.494	0.091
2.0	0.01013	0.1017	0.0464	0.465	0.370	0.503	0.496	0.092
3.0	0.01223	0.1189	0.0406	0.493	0.372	0.505	0.498	0.093
4.0	0.01282	0.1235	0.0384	0.498	0.372	0.502	0.500	0.094
5.0	0.01297	0.1246	0.0375	0.500	0.372	0.501	0.500	0.095
∞	0.01302	0.1250	0.0375	0.500	0.372	0.500	0.500	0.095

4.3. VACCUM TEST

The tested areas are accepted since no continuous bubbles formation is observed through all the bottom area of the tank. Which allow then to proceed for further steps of doing the thickness examination by the Ultrasonic measurements.

4.4. ULTRASONIC TEST

The ultrasonic test carried out to determine the thickness through all the flooring area of the tank and so depict a clear image about how it look and allow for further evaluation. The following graph in figure 4-3 summarize the results readings of 261 readings of all the area of the tank bottom for both TK-8 and TK-7 with a trend line slope equation of :

$$y = 0.0014\boldsymbol{x} + 4.9062 \tag{4.8}$$

for TK-8 and,

$$y = 0.0002\boldsymbol{x} + 4.1029 \tag{4.9}$$

for TK-7.

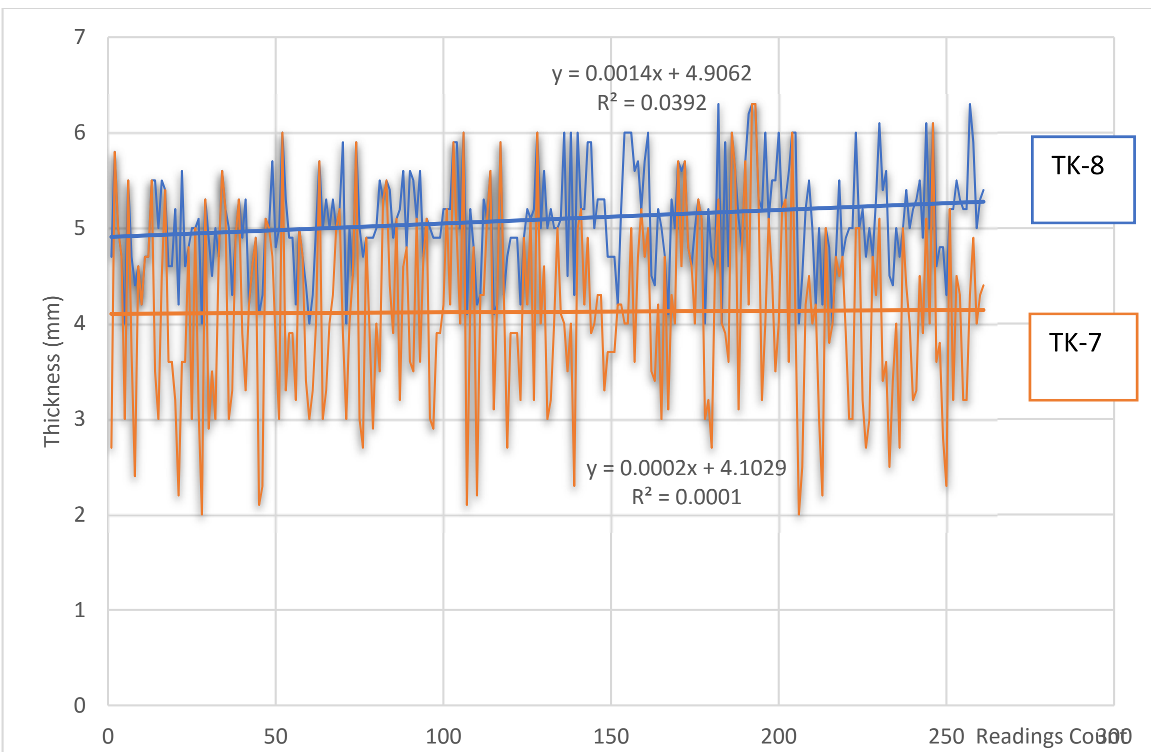


Figure 4-3: Thickness readings for TK-8 and TK-7

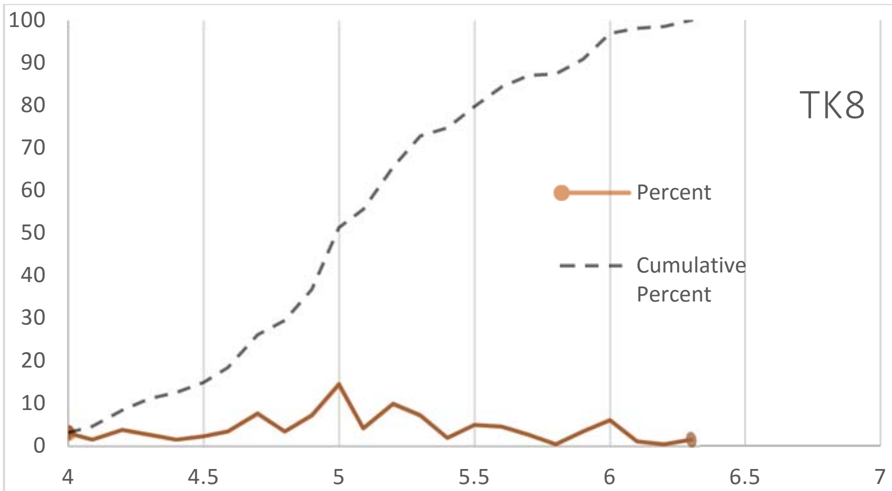
4.5. STATISTIACAL ANALYSIS

Table 4-6 below shows the frequency, valid and cumulative percent of the thickness readings of TK-8 and the thicknesses with higher occurrences are (5, 4.7, 5.3, 4.9, 6) mm with a percent of (14.6, 7.7, 7.3, 7.3, 6.1) % respectively, this give an indicator that the reduction in thickness occur gradually through almost the tank bottom area or in other words this occur within a close percentage around an averaged value of 5.1 mm for the thickness.

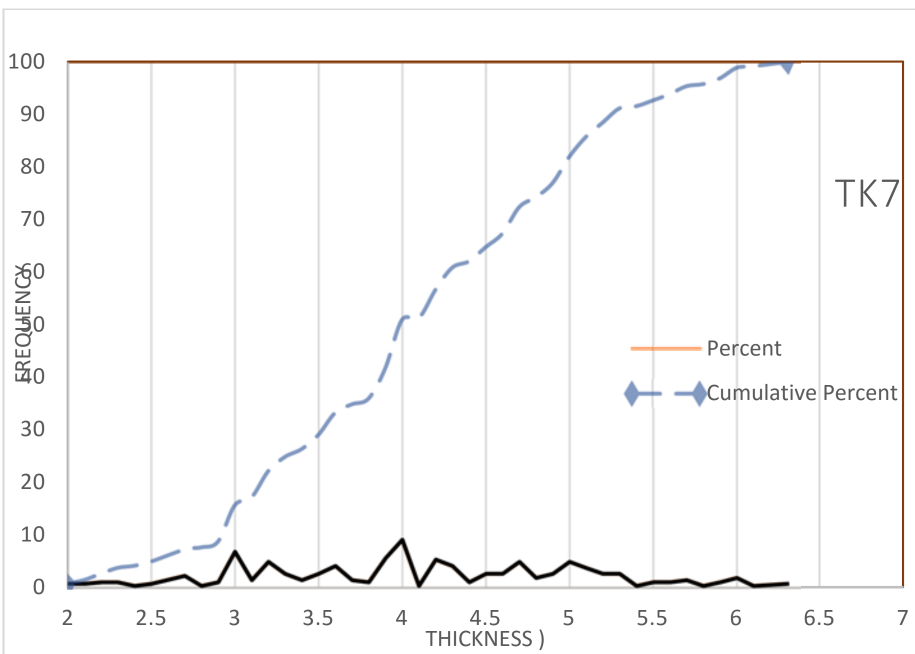
Table 4-6: Frequency, percentages and cumulative percent for TK-8.

Thickness (mm)	Frequency	Valid Percent	Cumulative Percent
4	8	3.1	3.1
4.1	4	1.5	4.6
4.2	10	3.8	8.4
4.3	7	2.7	11.1
4.4	4	1.5	12.6
4.5	6	2.3	14.9
4.6	9	3.4	18.4
4.7	20	7.7	26.1
4.8	9	3.4	29.5
4.9	19	7.3	36.8
5	38	14.6	51.3
5.1	11	4.2	55.6
5.2	26	10	65.5
5.3	19	7.3	72.8
5.4	5	1.9	74.7
5.5	13	5	79.7
5.6	12	4.6	84.3
5.7	7	2.7	87
5.8	1	0.4	87.4
5.9	9	3.4	90.8
6	16	6.1	96.9
6.1	3	1.1	98.1
6.2	1	0.4	98.5
Total	261	100	100

The data given in table 4-6 above are graphically represented for TK-7 in figure 4-4 (a) and TK-8 figure 4-4 (b) respectively, the dotted lines represent the cumulative frequency and the continuous line illustrate the percent of each reading.



(a)



(b)

Figure 4-4: Thickness and Cumulative Frequency for TK-8 and TK-7

Furthermore, figure 4-5 indicates that the distribution of the measured thick ness of both tanks that tend to be normally distributed around the normal curve, the skewness is 0.07 and 0.01 for TK-8 and TK-7 respectively, which illustrated with the other statistical parameters include the mean and standard deviation in table 4-7.

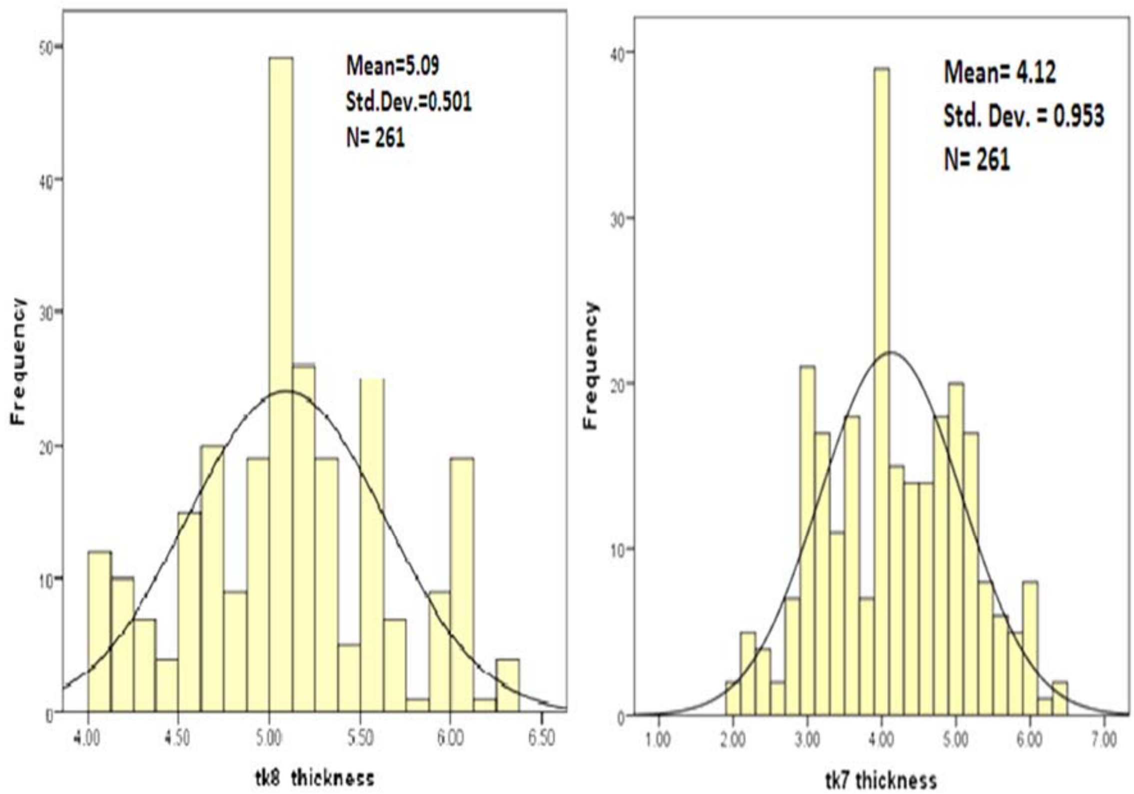


Figure 4-5: Comparison of the distribution of the data of thickness around the normal curve for TK-8 and TK-7.

An important indicator given in table 4-7 is that the percentiles which indicate that less than 10% of the measured thickness equals to or less than 4.3mm for TK-8 and the thickness of 2.9mm for TK-7. On the other hand, only 10% of the thickness were equals to or greater than 5.9mm for TK-8 and 5.3 mm for

TK-7 in other word 90% of the thickness fall between 4.3mm and 5.9mm for tank 8 and between 2.9 and 5.3 for tank 7. Calculating the central tendency measures for TK-8 and TK-7 considering the sample as the readings of thickness for both tanks, table 4-7 shows the results including mean and standard deviation that involved for the determination of the coefficient of variation.

Table 4-7: Comparison of statistical parameters for TK8 and Tk7.

	TK-8	**TK-7**
Mean	**5.091**	**4.123**
Std. Error of Mean	**0.03351**	**0.05898**
Median	**5.0569**	**4.0760**
Mode	**5**	**4**
Std. Deviation	**0.501**	**0.95292**
Variance	**0.293**	**0.908**
Skewness	**0.07**	**0.01**
Std. Error of Skewness	**0.151**	**0.151**
Kurtosis	**-0.395**	**-0.591**
Std. Error of Kurtosis	**0.3**	**0.3**
Range	**2.3**	**4.3**
Minimum	**4**	**2**
Maximum	**6.3**	**6.3**
Sum	**1328.76**	**1076**

Percentiles	**TK-8**	**TK-7**
10	**4.3**	**2.9438**
20	**4.7**	**3.207**
25	**4.7**	**3.3682**
30	**4.9**	**3.5644**
40	**5**	**3.9149**
50	**5**	**4.076**
60	**5.2**	**4.3443**
70	**5.3**	**4.7022**
75	**5.5**	**4.8708**
80	**5.6**	**5.0113**
90	**5.9**	**5.31**

4.5.1. COFFICIENT OF VARIATION

As from equation (2.6), and the data from table 4-7 taking the mean as (5.091) and the standard deviation as (0.501) substituting this values the following resulted:

For TK-8:

$$\text{COV}_{(\text{TK-8})} = \frac{\mathbf{0.501}}{\mathbf{5.091}} = 0.098409$$

For TK-7:

$$\text{COV}_{(\text{TK-7})} = \frac{\mathbf{0.952}}{\mathbf{4.123}} = 0.2309$$

A comparison between the results of the COV for TK-8(0.098409) which fall below the governing limit and TK-7 (0.2309) of give indication that the corrosion behavior for tank 8 fall below the governing limit of 10% and the average of the measurements of thickness for the 261 reading (**5.091 mm**)is considered homogenous (critical thickness profiles) and acceptable for using it for any calculation of thickness involving a reference value, whereas the case for tank 7 the COV value is much beyond that of acceptance accordingly the readings of the thickness were not considered for further processing.

4.5.2. CORROSION RATE

The corrosion rate per year was determined using the formula:

$$\textbf{\textit{Corrosion Rate}} = \frac{\textbf{\textit{Original thickness}} - \textbf{\textit{Average mesured thickness}}}{\textbf{\textit{Number of years}}} \qquad \textbf{(4.13)}$$

taking the formula with original thickness of 8mm and average measured thickness of 5.1 and 4.1 for TK8 and TK-7 respectively the rate will be 0.145 mm. year $^{-1}$ for 20 years for TK-8 and 0.195 mm per year for TK-7.

Also in case of considering the corrosion occur in faster rate i.e. the corrosion starts to occur after the deterioration of the protective coating layer due to scratching until it’s removal within a period of 3 to 5 years then the rate will be 0.193 mm per year for TK-8 and 0.390 mm per year , these rates generally were accepted since the average literature value for corrosion rate of gas oil tanks is 0.5 mm per year, diesel oil tanks is 0.5 mm per year and fuel oil tanks is 0.28 mm per year. Table 4-8, and figure 4-5 give the gradual corrosion rate over 20 years of equal inspection periods of 5 years for TK-8.The tracing of the corrosion over years it could be clearly observed that the rate is negligible in the first five years , then tend to increase slightly through the next five years after that it increased in a greater and almost stable manner for the next inspection intervals, and this might accepted and explained as the original thickness of the plates treated with a protective coating that's scratched till totally removed as the tank in service.

The thickness of bottom accordingly might be determined depending on this results and a linear trend equation formulated as:

$$\mathbf{y = -0.1826x + 9.105} \qquad (4.14)$$

and,

$$\mathbf{y = -0.0139x^2 + 0.1649x + 7.3675} \qquad (4.15)$$

where ,

y represents the value of thickness for a specific year. And,

x stands for the specified year.

Following the same procedure for TK-7 the linear trend line equation will be:

$$\mathbf{y = -0.201x + 8.6842} \qquad (4.16)$$

equations (4.14) up to equation (4.16) could be used for predicting the average of the thickness for any future thickness determination with a precise results considering the reference of the trend lines for the described tank. This could be obviously seen at the pint at the end of the curve in which a prediction of the thickness in the next five years achieved depending on the inspection data record in the 20 passed year, which give a thickness prediction of 2.8 mm which in terms fall within the allowable range of safe use.

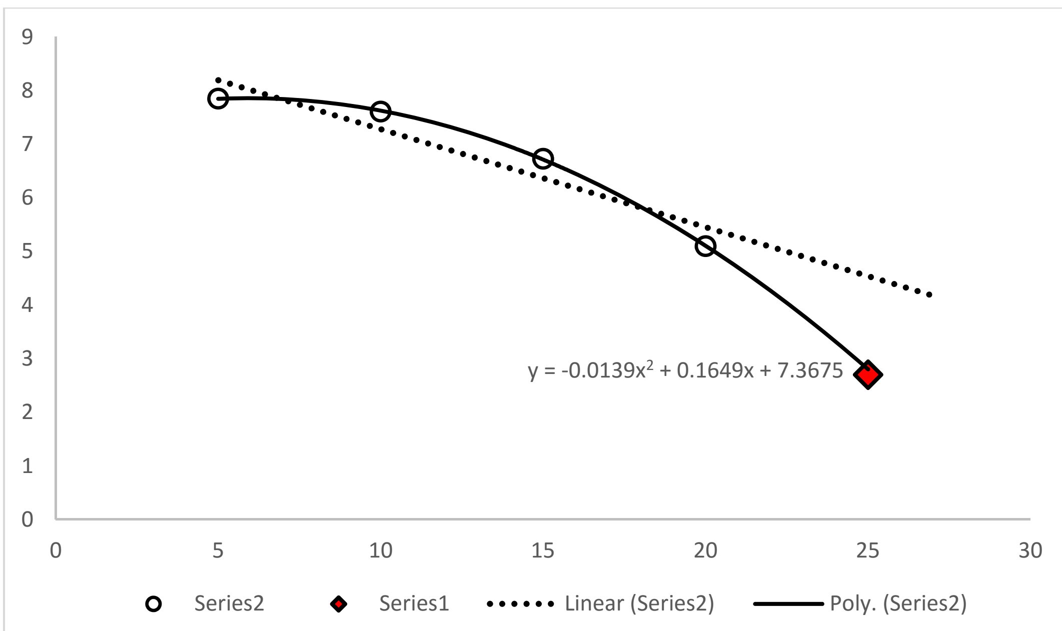


Figure 4-6: Actual and Averaged corrosion rate over 20 years for TK-8.

4.6. FINITE ELEMENT RESULTS

The following data in table (4-8) below are the parameter of the material A-36 structure steel which taken in combination with the data from table (3-1) illustrating the distribution of the different forces acting on the bottom and the

shell, the package of this data taken to define the boundary conditions for the model, executing the simulation and, generating the results of the FEM.
The cases from case 1 up to case 5 in table (3-1) are represent cases that a change of the forces due to the change of the model floor thickness which in terms leads to change of weight that computed and converted to its equivalent force values.

Table 4-8: The parameters of A-36 structural steel used and for simulation.

Density	7850 kg m^-3
Coefficient of Thermal Expansion	1.2e-005 C^-1
Specific Heat	434 J kg^-1 C^-1
Thermal Conductivity	60.5 W m^-1 C^-1
Resistivity	1.7e-007 ohm m
Temperature C	22c
Young's Modulus Pa	2.e+011
Poisson's Ratio	0.3

The finite element analysis was successfully conducted, figure 4-6 shows that equivalent Stress (Von-Mises stress) the maximum values concentrated at the area of the joining between the shell and bottom and extended for about 500 mm horizontally at the lower side of the bottom (give the minus sign) showing that the it's a tension stress in nature, it also goes vertically with a peak value in the first lower shell coarse and decreased gradually for the next upper coarses which in term may result the well-known phenomena called Elephant Foot.

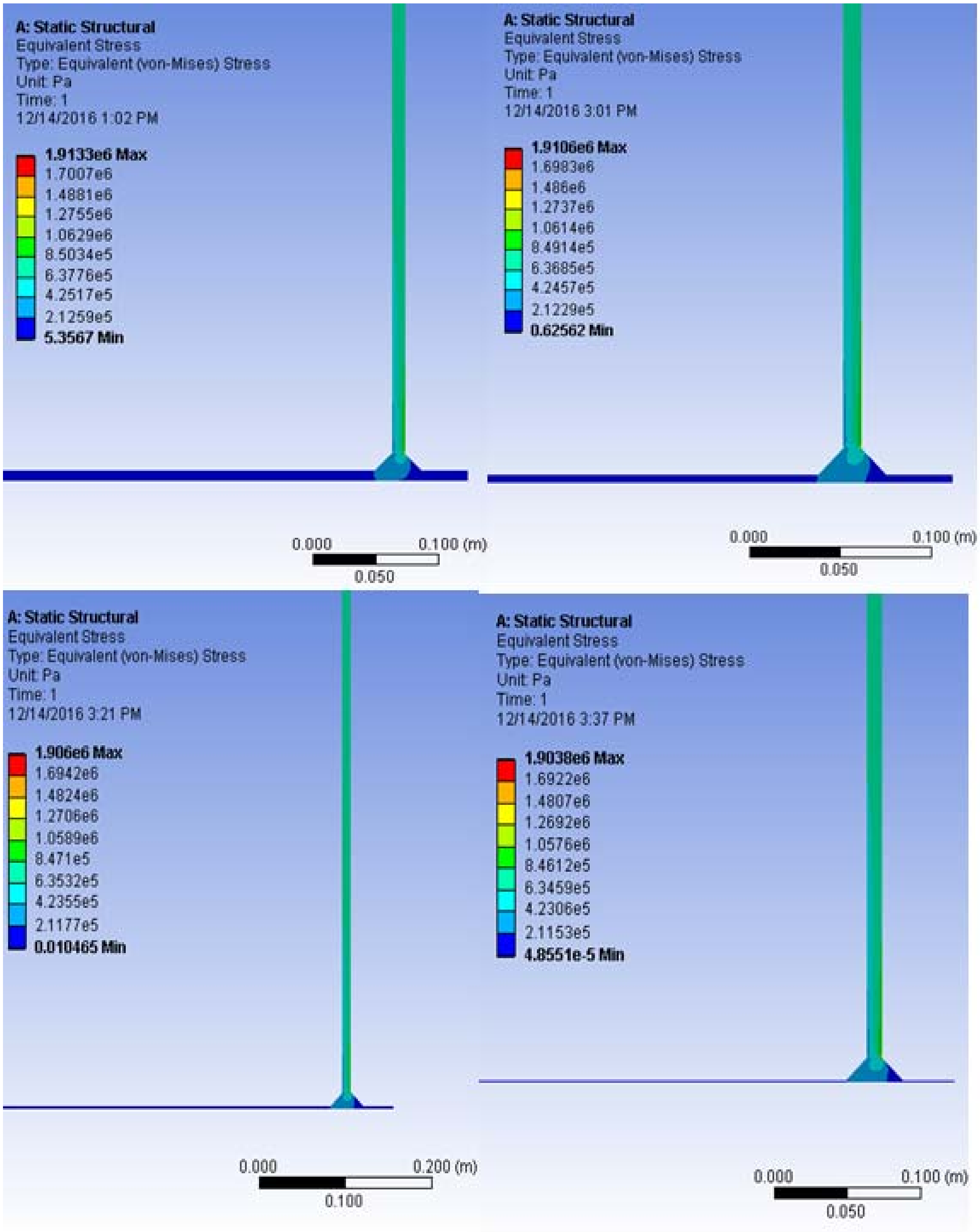


Figure 4-7: Equivalent Stress (Von-Mises stress)

Table 4-9: FEM results summary for the different thicknesses averages.

Thickness (mm)	Type	Total Deformation $X10^{-5}$(m)	Equivalent Elastic Strain (m/m)	Maximum Principal Elastic Strain	Minimum Principal Elastic Strain	Equivalent (von-Mises) Stress(Pa)	Maximum Principal Stress(Pa)	Minimum Principal Stress(Pa)
8	Min	0.	2.6783e-011	-3.1543e-010	-1.0104e-005	5.3567	-3.041e+005	-2.2836e+006
	Max	1.5447	9.5958e-006	3.7849e-006	-2.5871e-011	1.9133e+006	66100	9.9074
6	Min	0. 0	1.3147e-011	-2.8792e-010	-1.0133e-005	2.6294	-3.0478e+005	-2.2896e+006
	Max	1.5446	9.6275e-006	3.8005e-006	-7.7754e-012	1.9193e+006	67717	2.7426
5.1	Min	0.	9.5309e-012	-2.6441e-010	-1.0098e-005	1.9062	-3.0268e+005	-2.2818e+006
	Max	1.5445	9.5934e-006	3.786e-006	-2.9927e-012	1.9125e+006	67011	1.0461
4.1	Min	0.	3.1281e-012	-2.194e-010	-1.0088e-005	0.62562	-3.0259e+005	-2.2796e+006 Pa
	Max	1.5445	9.5844e-006	3.7821e-006	-9.4207e-013	1.9106e+006	67394	0.57296
2.7	Min	0.	9.3771e-014	-1.404e-010 m/m	-1.0063e-005	1.0465e-002	-3.0053e+005	-2.2737e+006
	Max	1.5444e-005	9.5615e-006	3.7742e-006	-1.6379e-014	1.906e+006	67267	2.1736e-002

Table 4-9 summaries the results of all the types of analysis conducted, its generally fall within the range of safe zone as the maximum total deformation is 1.544 e^{-6} m. which is considered negligibly small and its almost remain constant as the thickness proceed to decrease, the same implies for the von-

Mises stress since its value increased slightly as the thickness reduced but for so far remain within the accepted limits. Which means that the bottom is safe to operate normally until the critical thickness profile reach 2.7 mm in case of not equipping the tank with a cathodic protection and until 1.7 mm when a cathodic protection system and leak detection systems installed.

4.7. COST ALTERNATIVES

To retain the tank in service there one of three alternatives to decide between either to made a complete replacement for the bottom plate and adding an annular plate with estimated cost of 142,460 USD, or to made a partial repair of the most deteriorated plates with the lowest thickness profile namely plates (**B ,C ,F ,I** and **,N**) in addition to equipping the annular plate with an estimated cost of 74,410 USD, the third is to made the partial repair with no annular plate with an estimated cost 59,910 USD, the third one is rejected since the analysis results shows that the tank with critical thickness of 5.1 mm is safe to operate but a stress concentration at the weldment position between bottom and shell and extended beyond evolve that strengthen the structure with an annular plate.

Tolerating between the first and second alternatives the decision be to made a partial repair since the predicted life for the bottom is expected to be minimum additional 15 years , the first five years with negligible or even no thickness reduction that is due to application of new protective coating layer at that time the inspection interval will determine the conditions of the bottom fitness moreover the down-time will noticeably reduce to 40 days and the rate of return on maintenance cost will be about 155 days.

Table 4-10: Comparison of Replacement Repair costs.

Complete replacement of bottom plates, with attaching an annular plate						Partial repair of bottom plate , with attaching an annular plate					
DESCRIPTION		MATERIALS			LABOUR EQUIPMENT & CONS.	DESCRIPTION		MATERIALS			LABOUR, EQUIPMENT & CONS.
		QTY	RATE	AMT				QTY	RATE	AMT	
A	ANNULAR PLATE 8mm X 1.5m X 6m	10	750	7500	7,000	A	ANNULAR PLATE 8mm X 1.5m X 6m	10	750	7500	7,000
B	BOTTOM PLATE 8mm X 2.5m X 10m	51	750	38,250	19,250	B	BOTTOM PLATE 8mm X 2.5m X 10m	5	750	3750	3,500
C	SUPPLY AND FIXING OF TANK ACCESSORIES (Shell & Roof Man holes, Dip Hatch, Sprinkler, Drain sump, etc)	LUMP SUM		12,500	4,000	C	SUPPLY AND FIXING OF TANK ACCESSORIES (Shell & Roof Man holes, Dip Hatch, Sprinkler, Drain sump, etc)	LUMP SUM		12500	4,000
D	SAND BLASTING TO SA 2.5 AND COATING: DFT 350µm	LUMP SUM		12,500	7,500	D	SAND BLASTING TO SA 2.5 AND COATING: DFT 350µm	LUMP SUM		3,700	2,000
E	TESTS Hydrostatic Testing X-ray/ NDT Calibration Vacuum Box Test (Floor Plates) Vacuum Box Test (Roof Plates) Dye Penetrant Test for Base & Annular Plates	LUMP SUM		8,000	7,500	E	TESTS Hydrostatic Testing X-ray/ NDT Calibration Vacuum Box Test (Floor Plates) Vacuum Box Test (Roof Plates) Dye Penetrant Test for Base & Annular Plates	LUMP SUM		4,500	7,500
F	EARTHING SYSTEM	LUMP SUM		4,500	1,500	F	EARTHING SYSTEM	LUMP SUM		4,500	1,500
G	CATHODIC PROTECTION (Sacrificial Anode)	LUMP SUM		3,800	2,660	G	CATHODIC PROTECTION (Sacrificial Anode)	LUMP SUM		3,800	2,660
H	CIVIL WORKS	LUMP SUM		3,500	2,500	H	CIVIL WORKS	LUMP SUM		3,500	2,500
SUB TOTAL				90,550	51,910	SUB TOTAL				43,750	30,660
TOTAL				142,460		TOTAL				74,410	

where the case when made a full bottom replacement, the expected life time is 25 years , the downtime is 90 days and the rate of return will be about 315 days according to the fair assessment of the costs to put the tank in service again with an effective use, and this option will be adopted for any new construction of tanks with the same capacity, appendix (A) give a detailed design layout for the new layout of the bottom plate and the annular plate, and table (4-10) give an overview of the cost breakdown for the first and second alternatives.

CHAPTER FIVE

CONCLUSION AND RECOMMENDATIONS

5.1. CONCLUSION

In the present work, the Coefficient of Variation (COV) is determined and used to quantifying and setting procedure to take a remedial decision against the corrosion effect on the operability and serviceability of bottom plates of a steel aboveground storage tank, the effect which is considered to be a serious threat to the tank structural integrity. The data of the analysis are collected as a readings of thickness through all the area of the tank bottom, processed statically and shows that the critical thickness profile represented by an averaged value for thickness could be reliably taken to consideration for further analysis through finite element when the COV is less than 10%,The finite element analysis result concise with the results of basic design limits, additionally it predicts the spots of stress concentration , which are all used to weight between complete replacement for the bottom plate and partial repair alternative which considered the most weighted compared to the full replacement with a cut-off of repair costs to 52%, minimizing the downtime to 44.4%, and the rate of return reduced to 49.2%.

5.2. RECOMMENDATIONS

During the course of this research, opportunities for further study to improve the understanding of how the integrity of the structure affected by the joint efficiency (welding), and the effect of the product stored in tank, sludge, applied coating, flushing method and type of corrosion behavior can impact tank life cycle. Recommendations on how future work can to address these considerations are presented in this section.

- Further study of the design layout with an annular plate with a consideration for another types of tanks with different capacities and service conditions.
- The effects of using of another construction material, setting a specific execution procedure, and investigate its impact on costs and integrity combination.
- More detailed evaluations of the effects of dynamic forces that formed due to loading/unloading. These evaluations should assess the effects of this forces regarding the operations stability and structure integrity.
- To improve the modeling of tanks, additional data should be gathered from tanks including:
  - More close inspection intervals to generate data logs that enabling more accurate calculations which in terms would refine better prediction results.
  - If more accurate representations of finite elements results are desired, an up-to-date licensed software package and high specification hardware would be required.

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APPENDIX A

A1. In this section a detailed layout for the re design of the bottom illustrated including the annular plate (ring plate).

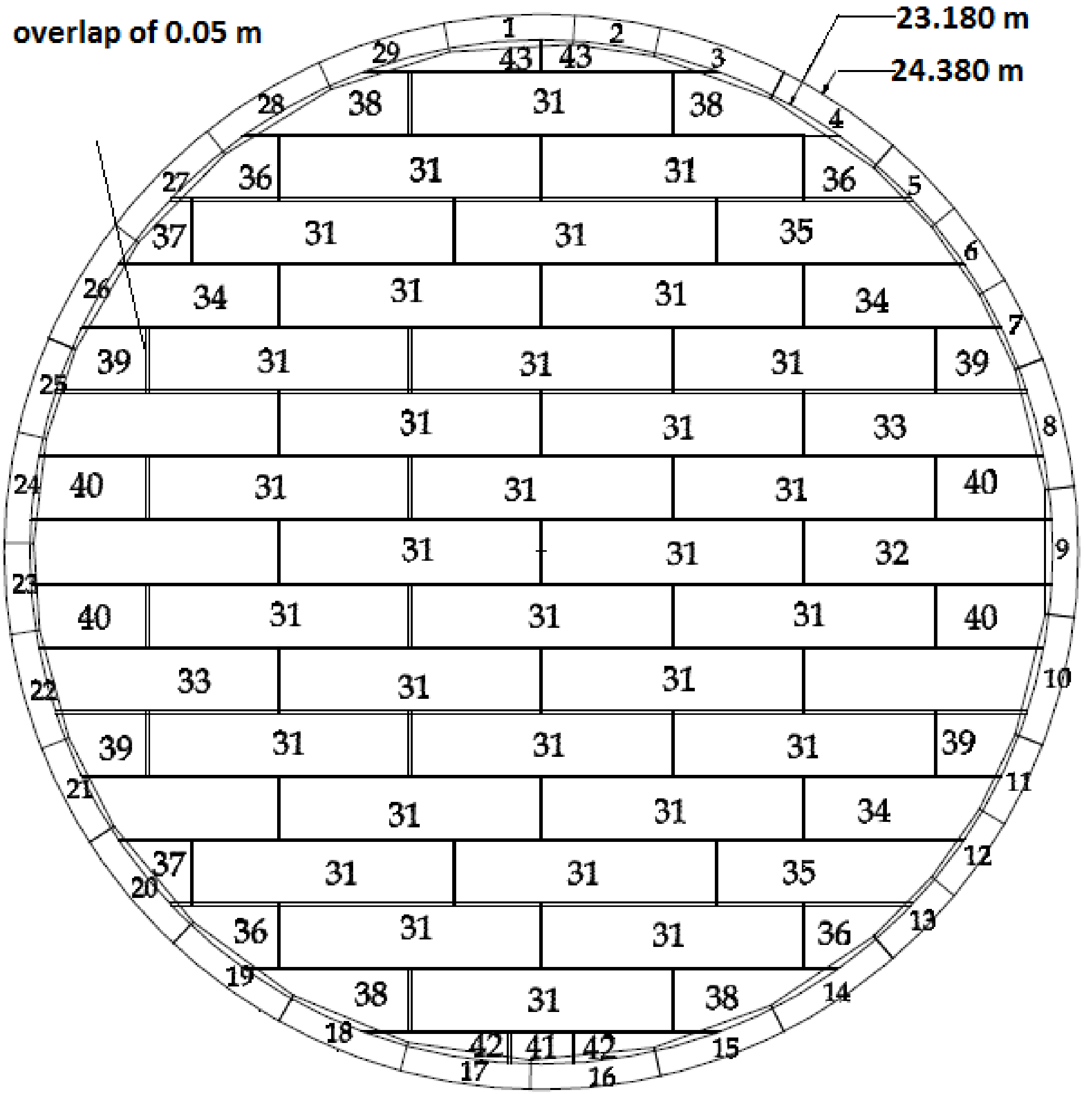

Figure A-1*: full development of the new bottom layout (plates number from 31 to 43) considering additional annular plate((plates* *number from 1 to 29)) lay on the bottom and welded to both of tank bottom and shell of TK-8 .*

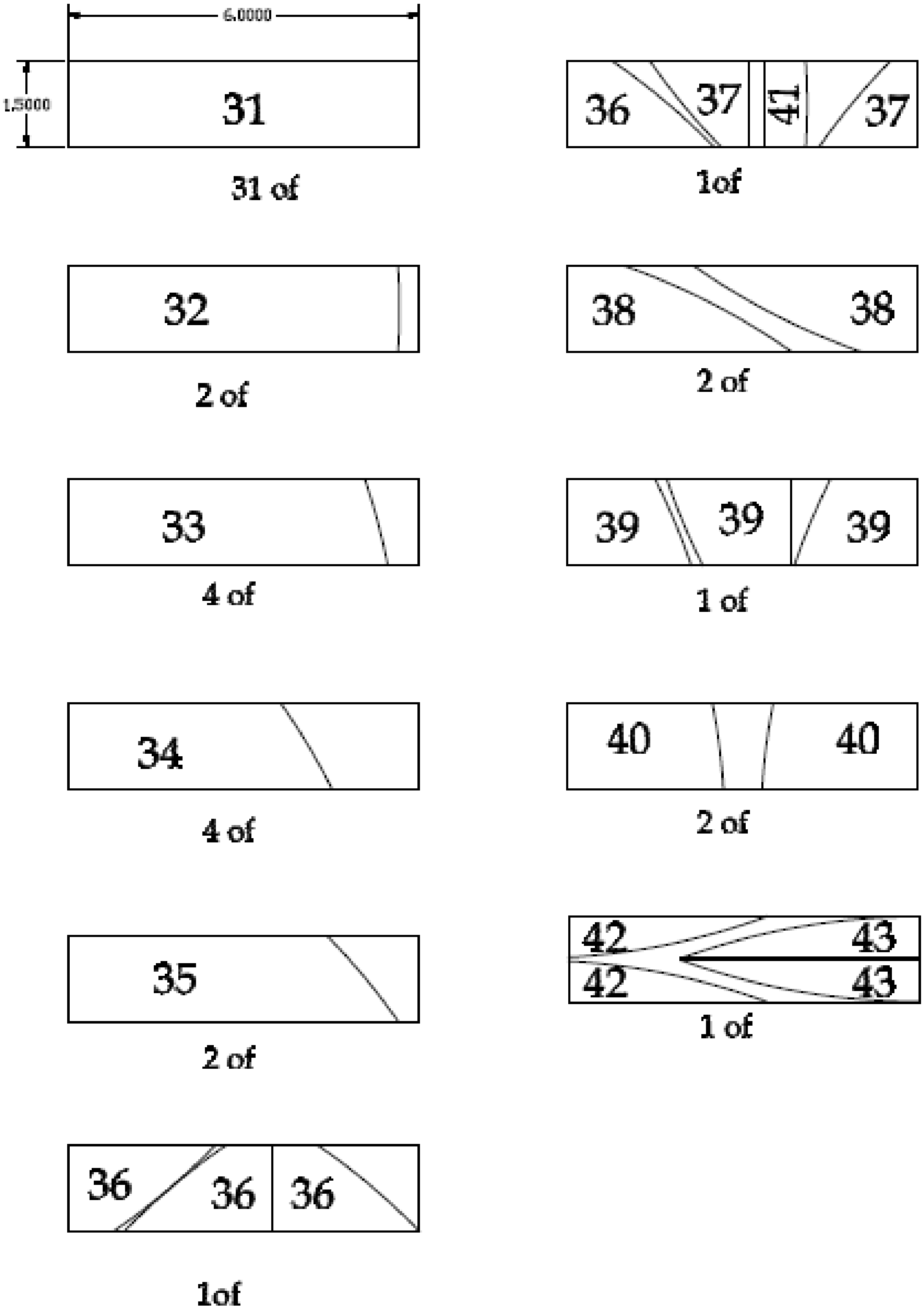

Figure A-2: Total of 51 1500mmx6000 mm plates for the whole bottomed area.

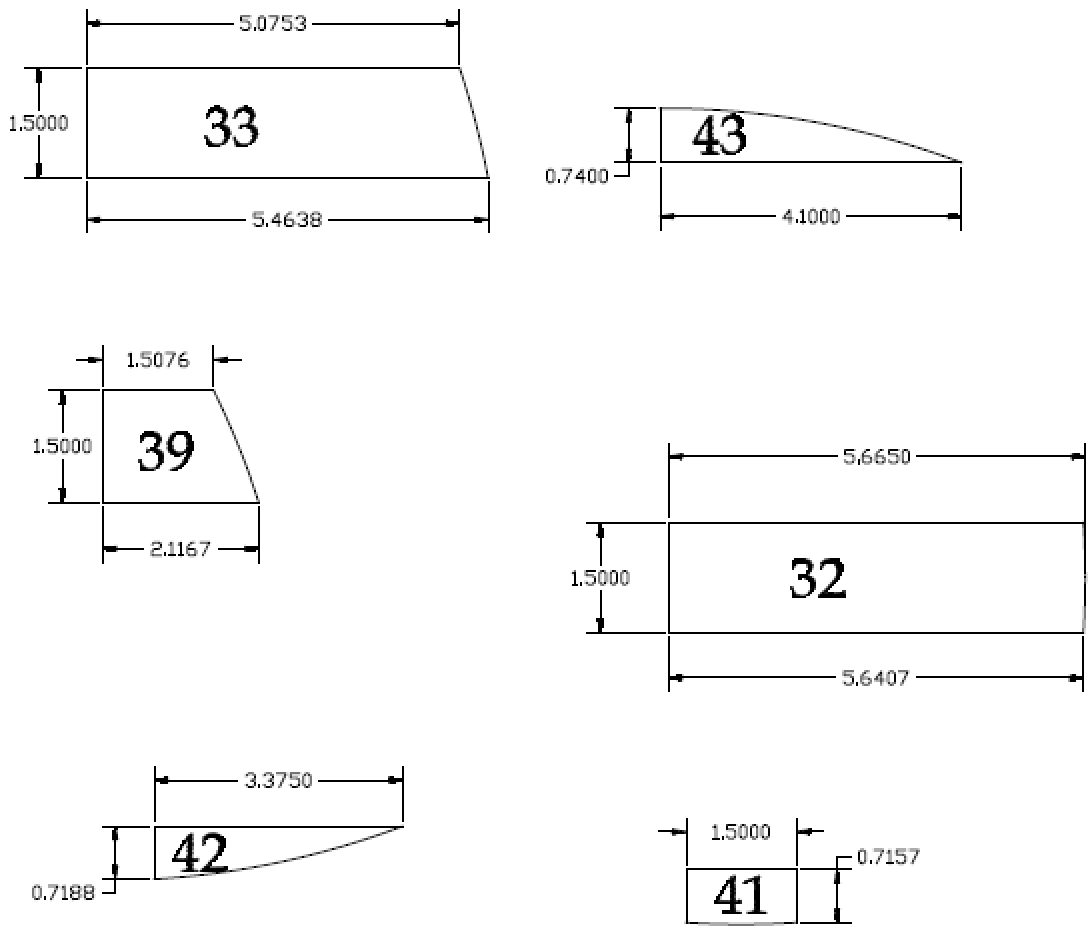

Figure A-3: Dimensions for the cutting of numbered plates (bottom).

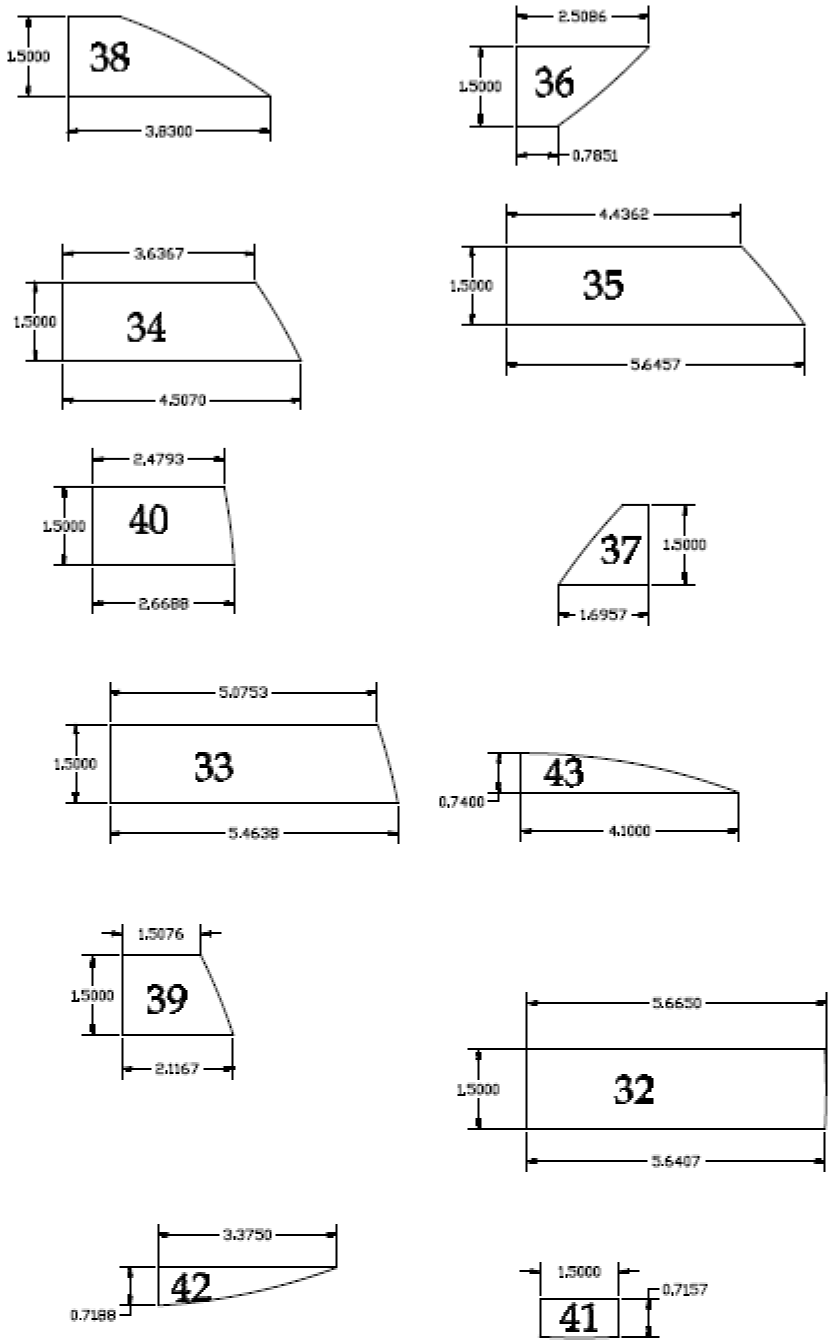

Figure A-4 : Dimensions for cutting of the numbered plates (bottom).

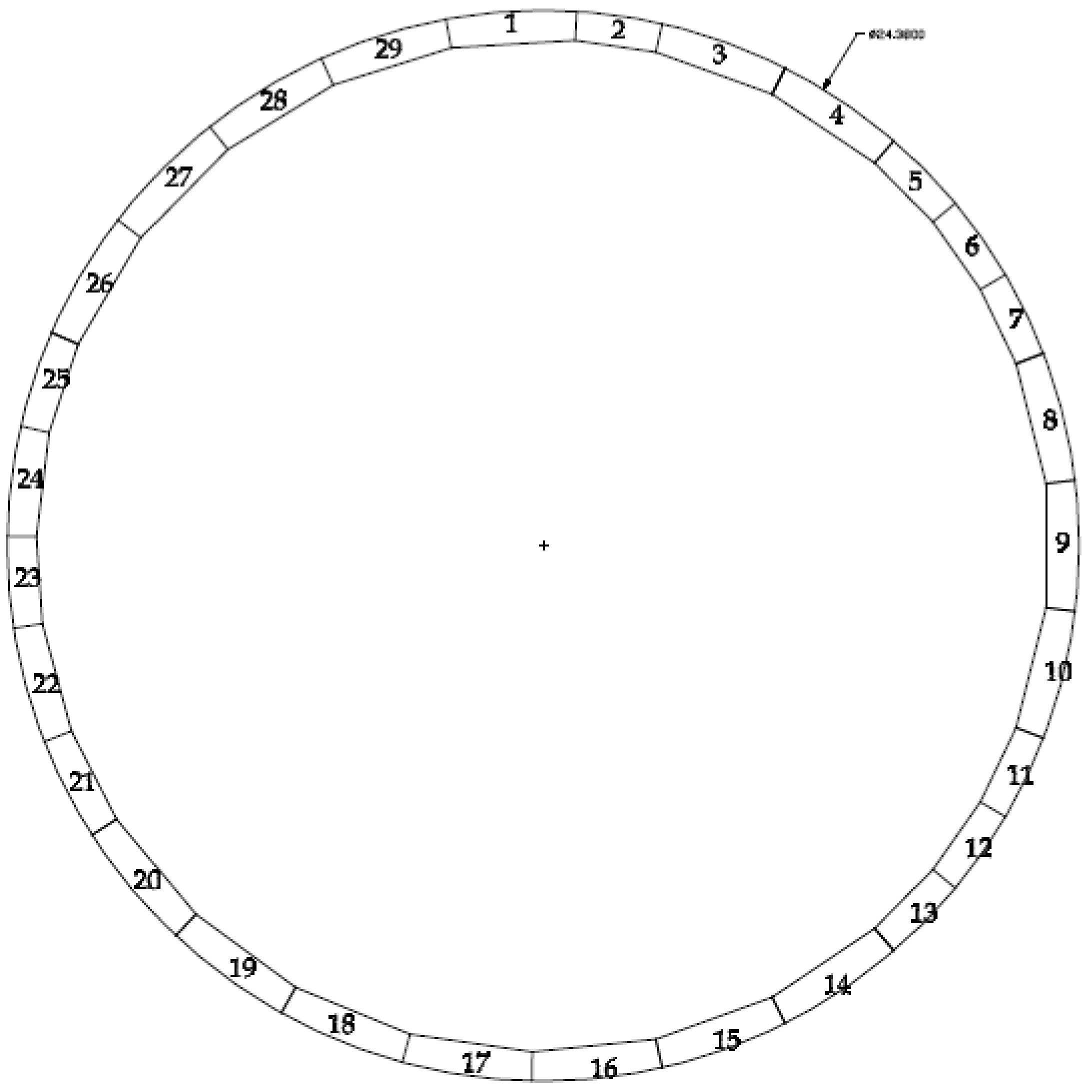

Figure A-5 : layout of the annular plate

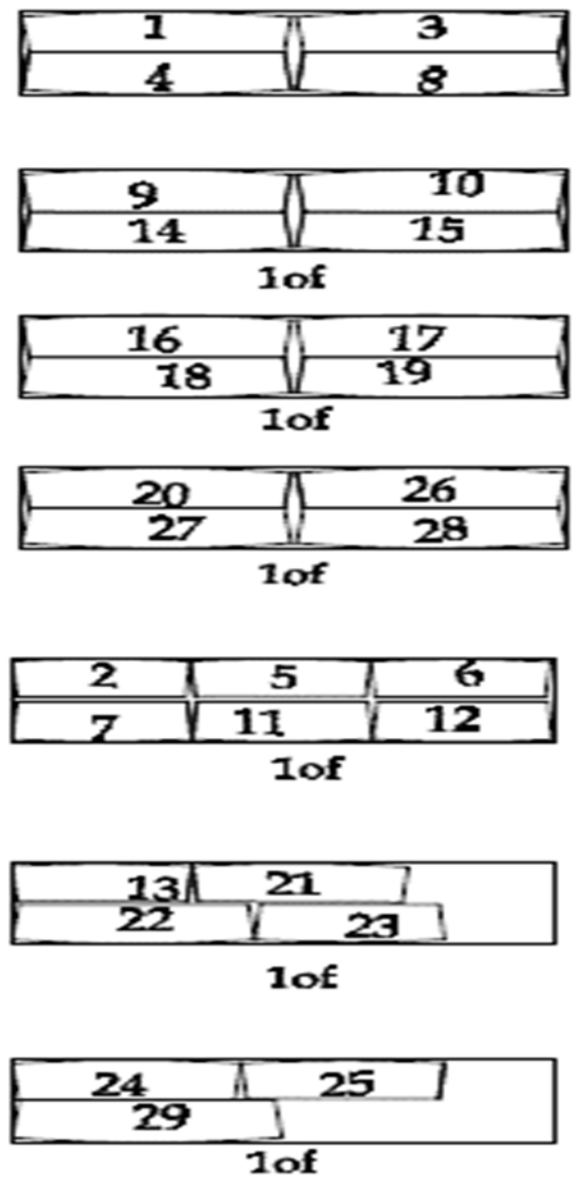

Figure A-6: *7* ***Nos****. plates of (1.5 x6) meter are required to complete the full crown of the annular ring with shapes illustrated.*

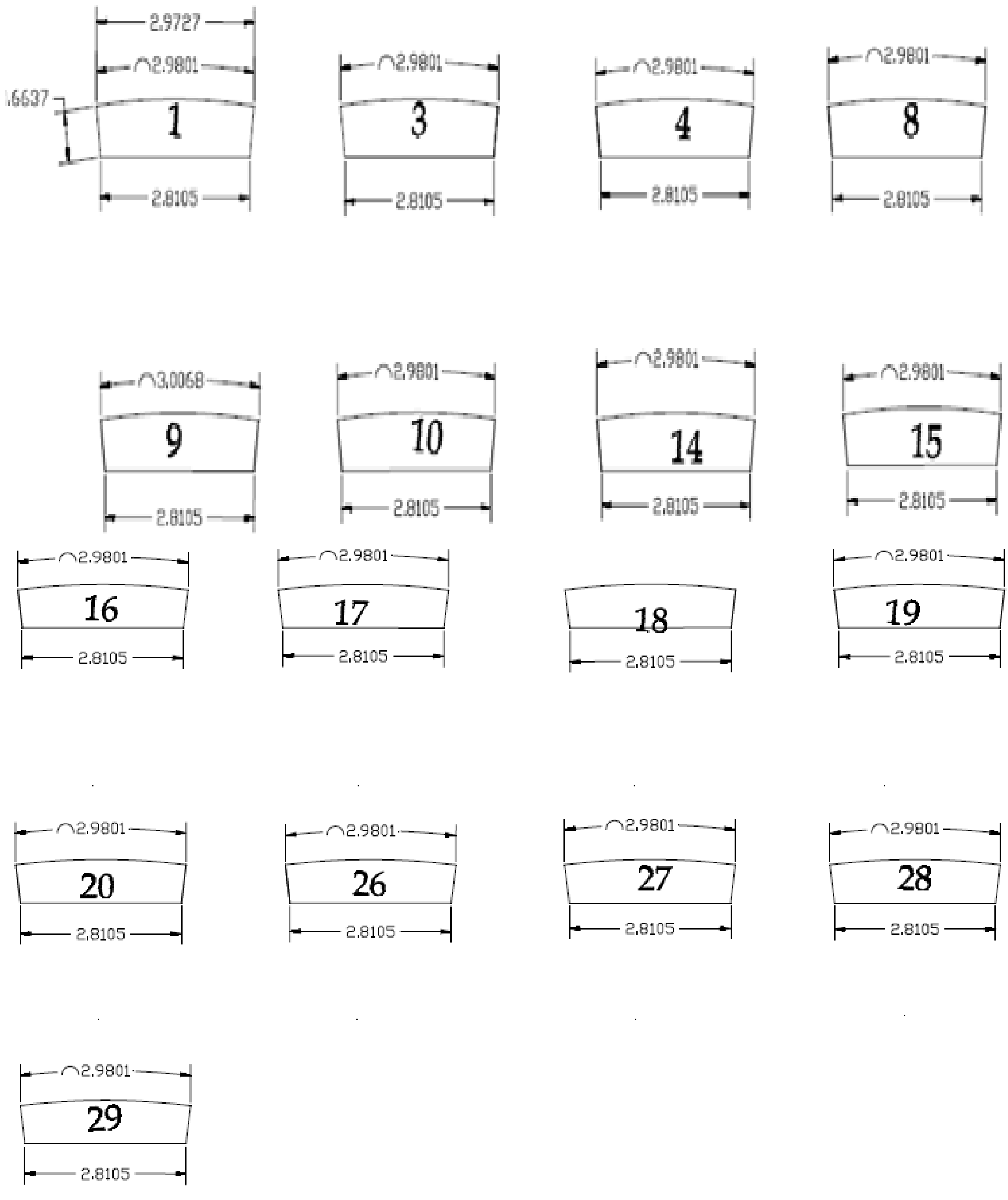

Figure A-7: *The Dimensions of the pieces of the annular ring (17 pieces with the largest area).*

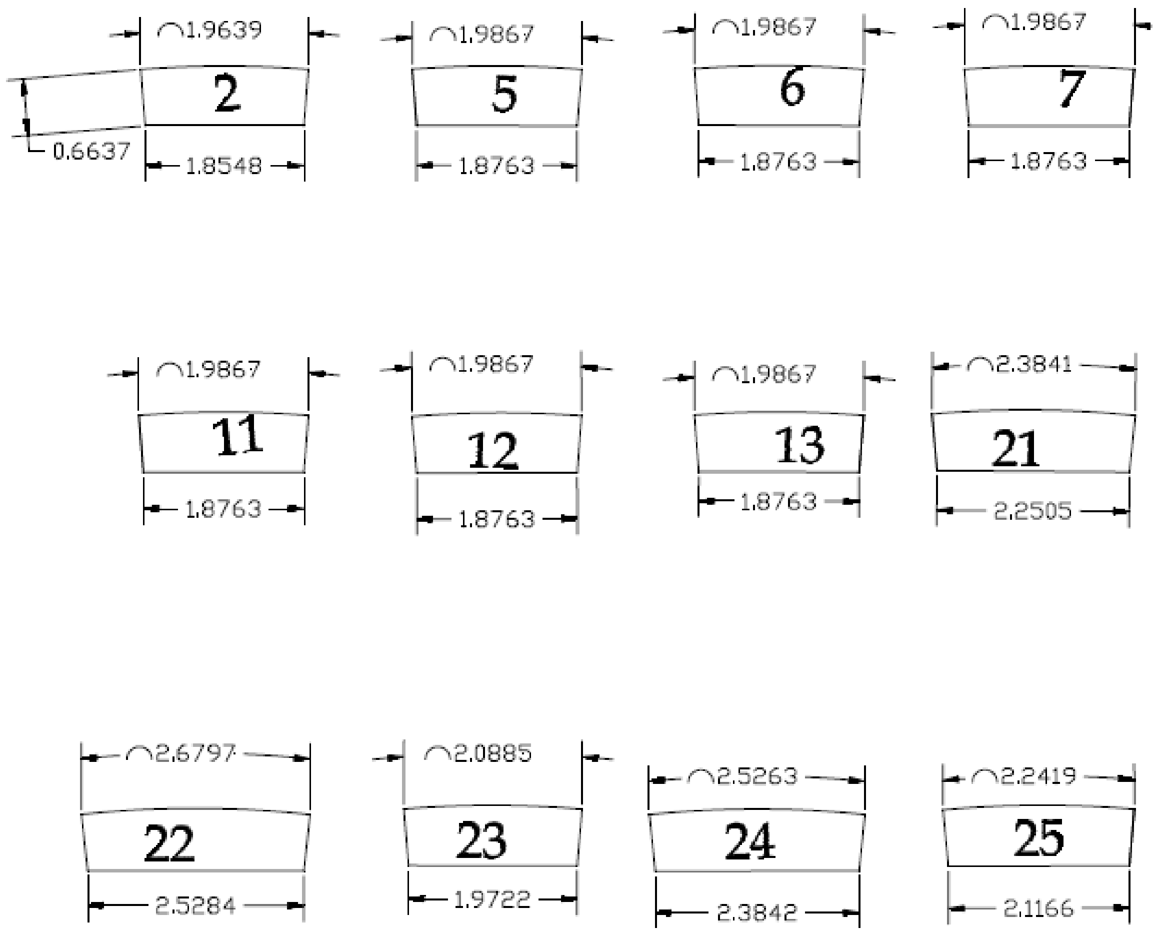

Figure A-8: *The Dimensions of the pieces of the annular ring (12 pieces with the smallest area).*

A2. Imperial formula used for the determination of the costs of the various items described in table (4.11)

Estimating cost with an empirical methods of costing are common practice for such types of equipments in which the cost calculated from the equations described below used for a +/- 25% budgetary cost.

Base Cost for CS Field-Erected tanks in SI Units

$$CB = EXP\ (9.369 - 0.1045 * \ln V + 0.045355 * (\ln V)2)$$

where:

CB = *Base Cost of the tank, USD,*

V = *Volume in m3, Lower Limit: 80 m^3, Upper Limit: 45,000 m^3***.**

N**ote**:

Cost Index (CI) for any year can be obtained from the Plant Cost Index data.

Note:

Cost of field-erected tanks includes the costs of platforms and ladders but not of foundations and other installation materials.