UNIVERSITEIT VAN PRETORIA
UNIVERSITY OF PRETORIA
YUNIBESITHI YA PRETORIA

The Impact of Technical Specifications on the Life Cycle Costs of Process Columns in Petrochemical Facilities

by

Keith S. Johnston

Submitted as partial fulfilment
of the requirements for the degree

Master of Engineering: Management of Technology (M.Eng(MOT))

In the Faculty of

ENGINEERING, THE BUILT ENVIRONMENT
AND INFORMATION SYSTEMS

University of Pretoria
Pretoria
South Africa
July 2007

ACKNOWLEDGEMENTS

The author gratefully acknowledges the contributions of the following people:

Prof. J Amadi-Echendu	-	Thesis Supervisor
Mr. E Lear	-	SASOL Cost Estimation
Mr. M Koopman	-	SASOL Synfuels Refinery
Mr. C Pike	-	SecMet Metallurgical Services

The SASOL Mechanical Engineering Department for the participation in the questionnaire.

TERMS OF REFERENCE

The thesis topic was generated by the author in **March 2005** as partial fulfilment of the requirements for the **Master of Engineering: Management of Technology Degree.** The proposal was drafted and submitted to the **Department of Technology Management** at the **University of Pretoria**. The proposal was accepted and commissioned under the supervision of **Prof. J Amadi-Echendu**.

The thesis combines **technology management**, in terms of technical specification requirements, with **asset management** in terms of **Life Cycle Costing**. The aim is to determine what the impact of technical specifications on the **Life Cycle Costs** (LCC) of **process columns** in petrochemical facilities have.

The basis for the research is the process columns located at the **SASOL Synfuels** complex in **Secunda South Africa**.

SYNOPSIS

Advances in materials technology, information and management systems have led to improvements in the engineering design, procurement, construction, installation and commissioning of process columns. The development of the front-end engineering design (FEED) process has led to the incorporation of best practices in the specification of equipment on projects during the design phase.

The aim of the research is to investigate whether technical specifications have an impact on the life cycle costs of process columns. Adding to the initial capital cost of equipment, in the form of technical specification requirements, in an attempt to reduce life cycle costs, is always challenged during the project phase of a product life cycle.

The principle of designing for the full product life cycle of process columns requires that consideration for both the project and operating life cycle be made at the stage of basic engineering. What is important to note is that the potential for life cycle cost savings at the beginning of a product life cycle is higher than during the operating life cycle. Figure S.1 illustrates this concept, and what is observed is that the potential for life cycle cost savings diminishes as the product life progresses over time.

Process columns were chosen as the type of equipment to be investigated based on the nature, size and complexity of the equipment when compared to other equipment on a processing unit. Process columns are amongst the highest capital cost pieces of equipment in petrochemical units and usually have many auxiliary pieces of equipment associated with it in a system i.e. reboilers, condensers, pumps etc.

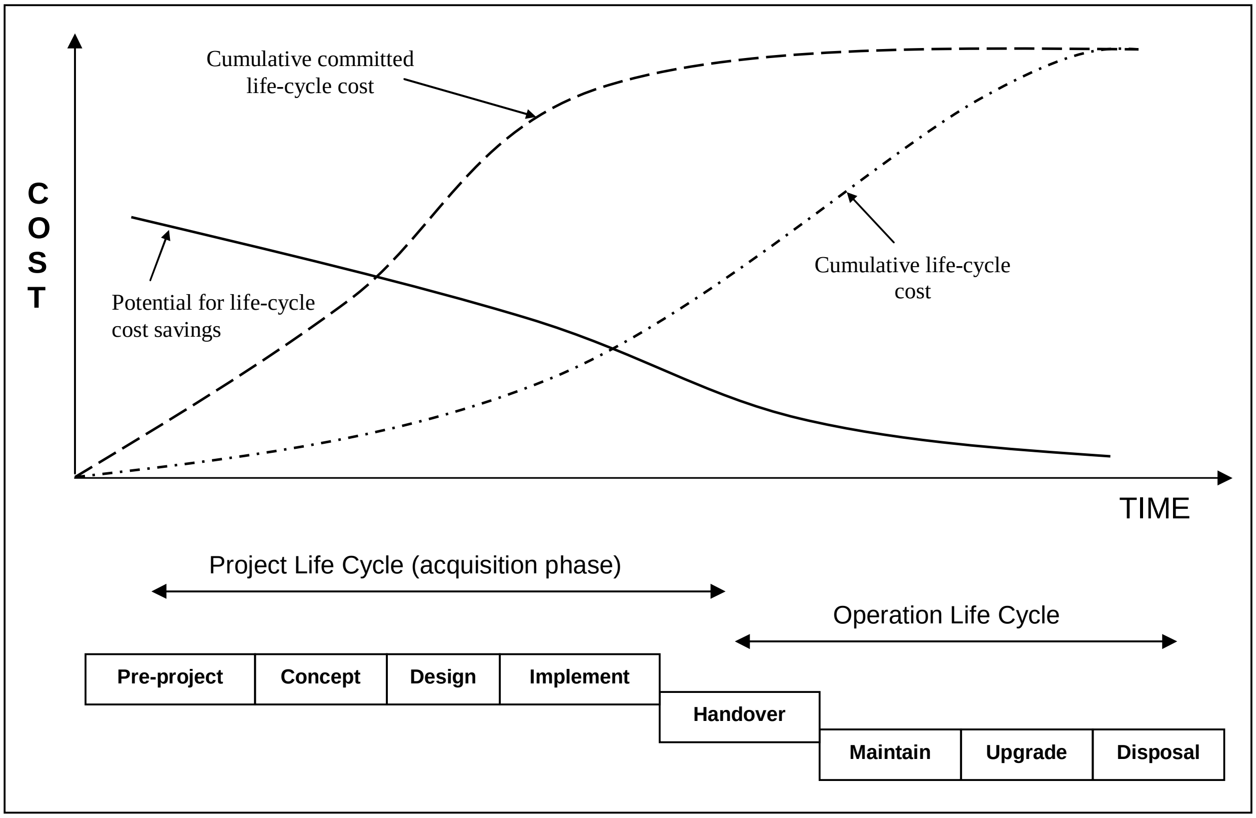


Figure S.1: Life Cycle Costs

Source: Sullivan et al (2003:35)

The objectives of the research are:-

i. *To examine technical specifications for pressure vessels based in user perceptions.*
ii. *To identify from historical data, the failure modes of process vessels in practice and to relate the failure modes to design and construction specifications.*
iii. *To analyse the costs recorded for the process columns chosen as part of the investigation.*
iv. *To establish the impact of project technical specifications on the total life cycle costs of pressure vessels*

The research hypothesis is that *there is positive correlation between the user requirements, as manifest in the technical specifications, applied during the project phase, and the total cost of ownership of process columns.*

The research methodology used was a combination of a Delphi analysis of the technical specifications as well as actual historical data on failures and costs for the process vessels. The strategy was to use three sets of data to substantiate the hypothesis.

The first data set was generated by extracting user requirements in the form of specifications that affect the technical integrity of process vessels. A group of users from the SASOL Technology Mechanical Engineering Department was asked to evaluate the specifications on a Likert scale of impact on technical integrity.

The second data set comprised of historical defects and repair reports for process vessels deployed by the SASOL Synfuels complex.

The third data set comprised of the historical costs recorded for the process vessels in the SASOL Synfuels Complex. The data was not complete as there were costs not recorded for defects/repairs instances. The sample was further reduced to the process columns with the most complete costing data.

On the analysis of the results from the data gathered, it was clear that requirements relating to the design and finishing of weld ligaments were perceived by the respondents to be most influential on the total costs of ownership. From the analysis of the defects/repair reports of vessels applied in corrosive environments, weld ligaments showed the highest occurrence of failures. The cost associated with this mode of degradation is the most common and recurring cost over the life cycle. Albeit that ignoring the time-value of money, the costs associated with weld ligament degradation seem minimal when compared to the initial acquisition cost of a process vessel.

The analysis of the defects/repairs reports together with the cost reports however displayed a consideration that was far more significant, and as high as twice the initial capital cost of the process column. Corrosion induced failure due to the presence of acids not anticipated in the process streams accounted for significant life cycle costs. Twenty-six of the seventy-eight columns had continuous corrosion problems as a result of the latent presence of acids which had not been anticipated during the project phase.

It was also noted that there was no SASOL guideline that specifies how materials should be selected in relation to the widest range of process stream conditions. So in terms of technical specifications, the factor actually had the most significant impact on LCC does not appear in user requirements such that correct material selection would be achievable.

Conclusions

The findings of the research show that:

- SASOL specifications regarding pressure vessels have not been written taking into consideration total costs of ownership, hence Life Cycle Costs are not capture in an effective way.
- A significant number of process vessels have experienced corrosion induced failures on weld ligaments thus corroborating user opinion that weld design is a significant factor that impacts on technical integrity of pressure vessels.
- Forty-eight percent of the process units in the refinery area have experienced defects on process columns as a result of corrosion. Hence corrosion is the root cause for most defects in the refinery area.
- The databases for costs per equipment number for the refinery area was populated sparse and inconsistently. An empirical correlation between technical specifications and the total costs of ownership could not be determined.
- For the columns where costing data was captured, it was observed that the highest cost area in the life cycle costs was due to corrosion and incorrect material selection. SASOL do not have specifications addressing material selection based on process streams.

Recommendations

Since technical specifications have a positive correlation with total cost of ownership, it is recommended that.

- LCC considerations in SASOL specifications need to be clarified by the originator of the specification
- A SASOL specification for material selection needs to be generated
- Data capture for costs associated with equipment needs to be centralised

Limitations and Further Work

The main limitation to achieve the objectives of the research was the completeness of the historical cost data for the process columns. The SASOL records for defects and repairs when compared with cost records revealed major omissions in costs of the vessel over the life cycle of the vessel.

An area for further research would therefore be to obtain a database of cost data for a different SASOL unit where the data is more complete for vessel's life cycle and to use this data together with the defects and repairs for that unit to determine empirically whether a correlation exists between technical specifications and life cycle costs.

Table of Contents

List of Illustrations

Figures

Tables

List of Symbols

ϵ_S	overall tray efficiency
N	number of trays
H	required height of each stage
H_a	vertical column height
T	total interest
P	principal amount
i	interest rate
n	interest period
F	future value
P	present value
N	analysis period

INTRODUCTION

1.1 Background

Advances in materials technology, information and management systems have led to significant improvements in engineering design, procurement, construction, installation and commissioning of columns and vessels for use in petrochemical applications. These improvements have largely resulted in increased reliability of columns and vessels.

These improvements also arise from the upfront specification and detailing of the facility in terms of design and manufacturing interfaces. What is now generally known as front-end engineering design (FEED) is a concerted effort to specify a facility in detail during the design phase of the project so as to engineer out potential problems. This is a major shift from the previous approach, where plants were built and then retrofit to rectify engineering flaws. The focus is now on good quality engineering upfront to minimise and reduce the impact of rectifying errors or oversights in the field during construction. To engineer on paper is far more cost effective than to alter hardware in the field.

This shift in philosophy has led to the rigorous development of specifications by end-users and engineering contractors alike to ensure that the FEED engineering process is consistent in applying sound engineering practice to designs as well as optimising design based on existing experience.

1.2 Specifications and Projects

The intent of this research is to investigate the impact of technical specifications on the **Life Cycle Costs** (LCC) of ***process columns*** applied in petrochemical facilities.

Initial specification of requirements is always a contentious issue on large capital projects, because there is a constant trade-off between the capital costs during the project phase against operating costs and technical integrity over the life cycle of the facility.

The environment for the research is a petrochemical facility and the focus is on the way in which technical specifications impact the total costs of ownership of pressure vessels.

In order to design and manufacture a pressure vessel to meet statutory requirements a designer will use a design and construction code listed in the Occupational Health and Safety Act (85 of 1993) e.g. ASME (American Society of Mechanical Engineers), BS (British Standards) or AD Merkblatter (German Code). Over and above the design code chosen, the user may, as part of the purchase order, stipulate specific requirements to be taken into account in the design and manufacture of the vessel. These requirements are usually in the form of user specifications. Specific user requirements may arise from unique safety and environmental conditions, past experience, maintainability, project and plant constraints etc.

This research aims to investigate the extent to which detailed apriori technical specifications actually impact the life cycle costs of pressure vessels.

1.3 The Principle of Designing for Life Cycle

The principle of designing for the *life cycle* of a product can be best described as designing for all aspects of the product from ‘cradle to grave’ (Burke (2001: 33-36)).

1.3.1 Product Life Cycle

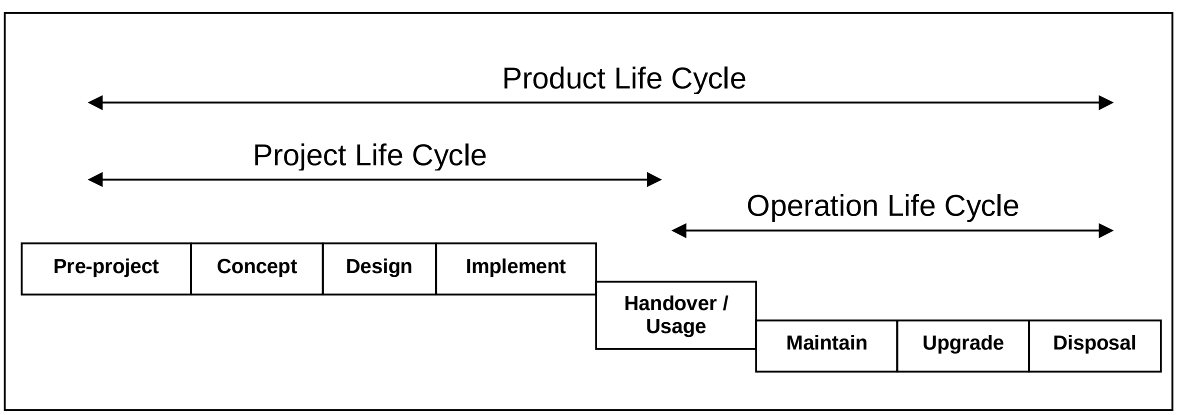
The life cycle of a product can be divided into very distinct phases. These phases account for all stages in development, manufacture and disposal of the product. Figure 1 illustrates the phases of the product life cycle.

Pre-project	**Concept**	**Design**	**Implement**	**Handover / Usage**	**Maintain**	**Upgrade**	**Disposal**

Source: Burke (2001:35)

Figure 1: Product Life Cycle Phases

For petrochemical plants, the average lifespan of pressure vessels, piping, compressors etc. is usually in excess of ten years. It is therefore common practice for a company to use various resources to account for the various phases of the life cycle. According to Burke (2001:35) the product life cycle can further be divided into a project life cycle and an operational life cycle, see Figure 2 below.



Source: Burke (2001:35)

Figure 2: Updated Product Life Cycle

It is common that responsibilities during the project life cycle are different from those during the operation of the facility. Thus the project and operation life cycles are considered separately by convention.

1.3.2 Project Life Cycle

As seen in figure 2 the project life cycle consists of the chain:- Pre-project engineering – Concept Development – Design – Implementation – Commissioning/Handover. Figure 3 is an illustration of the SASOL business development and implementation model on which the life cycle development of large capital project is based.

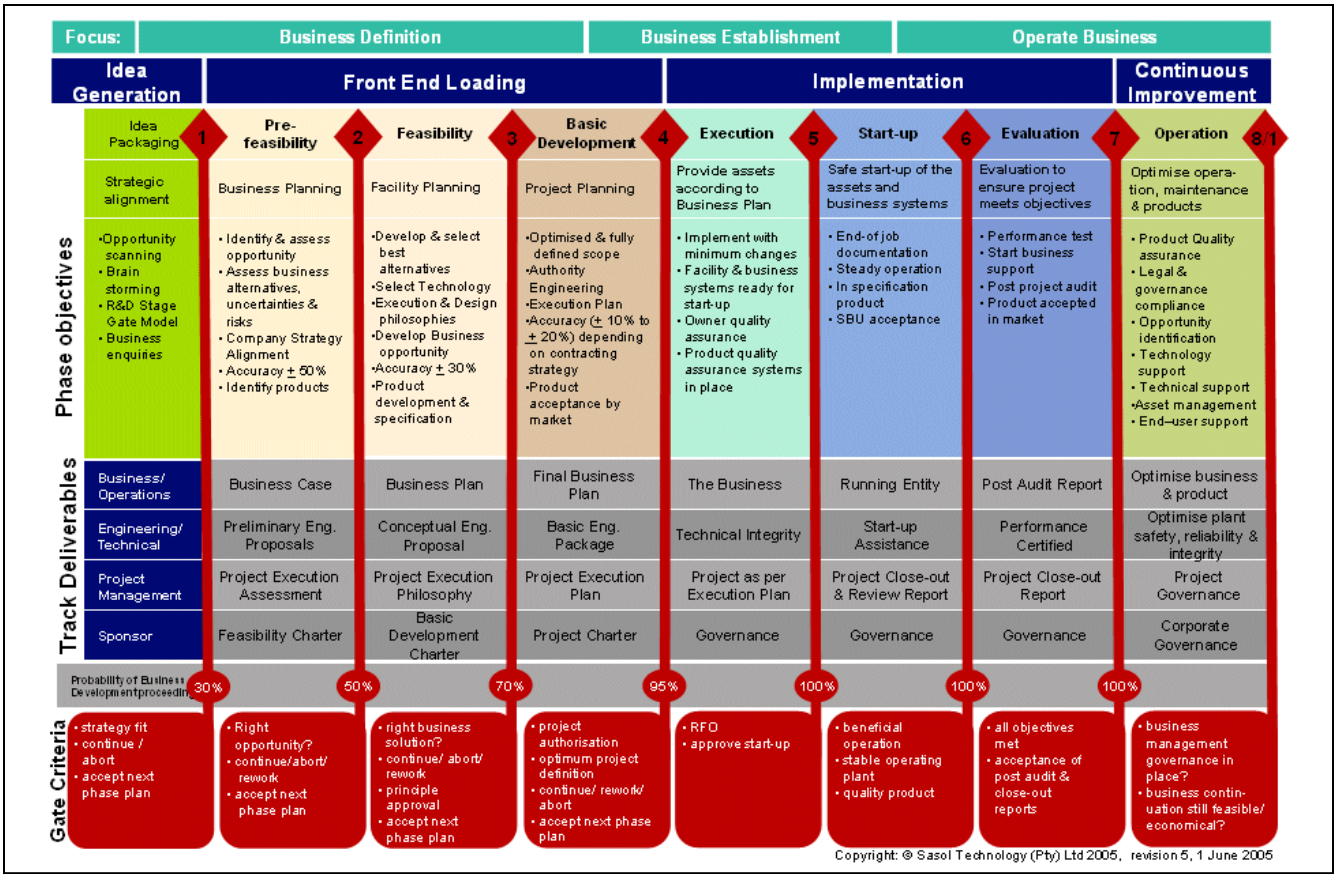


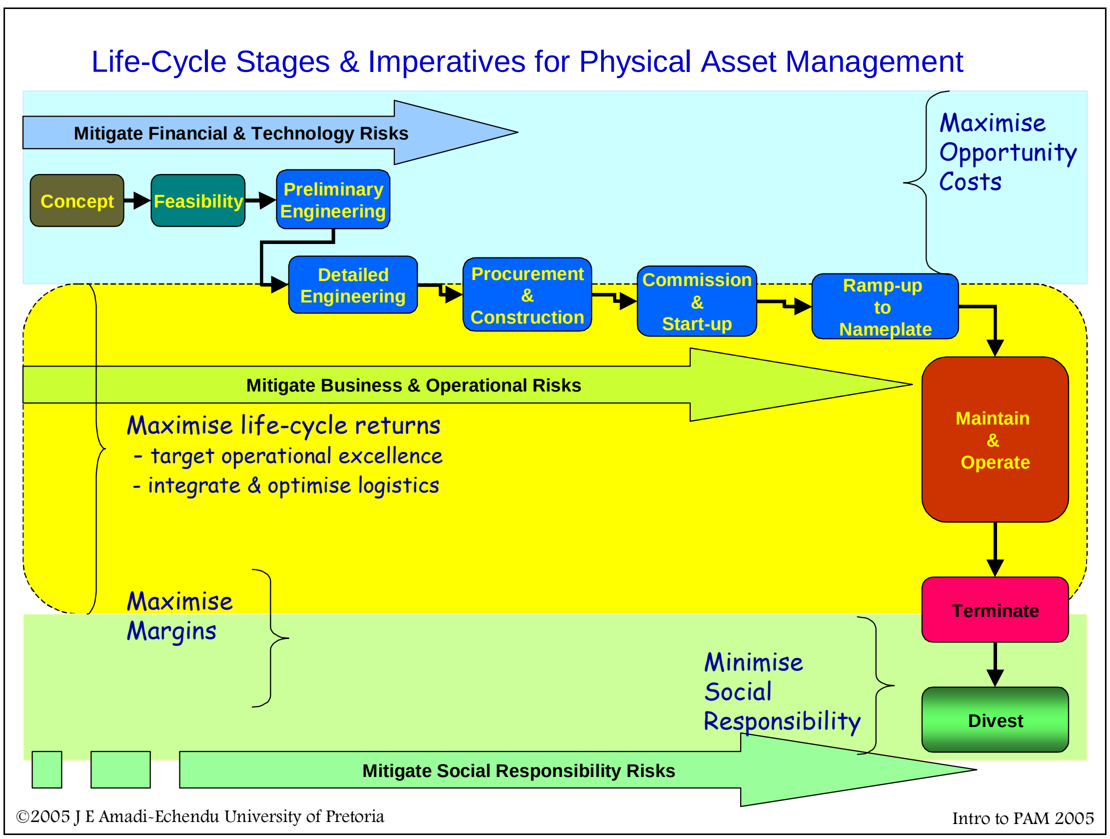
Figure 3: SASOL Business Development and Implementation Model

On large capital projects, the project engineers execute this phase of the product life cycle as a separate activity and then handover the facility to their operations counterparts. In a large petrochemical company like SASOL, project execution and operation are usually set up as two distinct organisations within the parent company. Further, the engineering contractor responsible for the detailed engineering of the project phase, in most cases do not own or operate plants.

1.3.3 Operation Life Cycle

This cycle consists of – usage - maintenance – upgrading/renewal/termination – decommissioning - disposal. Maintenance, refurbishment and renewals are core during this phase and can directly be linked to decisions made earlier during the project life cycle.

An environment where there is a good link between the project stages and the operations stage enables transfer of knowledge and communication between the project and operations team.



Source: Prof. JE Amadi Echendu, University of Pretoria

Figure 4: Life-Cycle Stages for Asset Management

Figure 4 re-emphasises the concept of life-cycle in the context of physical asset management.

1.4 Life Cycle Costs

The life-cycle cost of a product can be linked to its life cycle over time (Sullivan, Wicks & Luxhoj (2003:33-36)). The associated costs are illustrated in Figure 5 below.

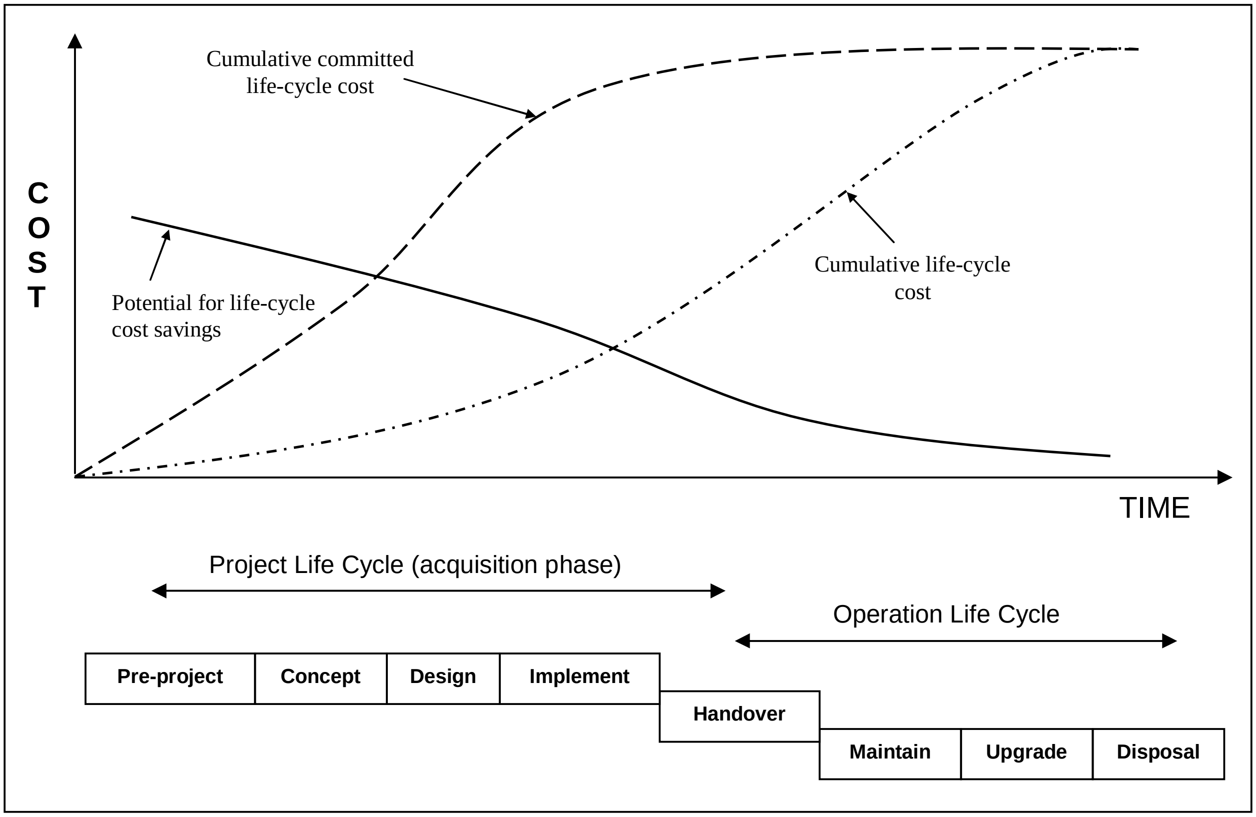


Figure 5: Life Cycle Costs for Products

Source: Sullivan et al (2003:35)

The term life cycle cost according to Sullivan et al (2003:33) refers to the summation of all costs, recurring and nonrecurring, related to a product during its life span. The costs, as with the life cycle, can be divided into two general time periods:-

i) the acquisition phase and
ii) the operating phase

During the acquisition phase of the project, most of the engineering will be handled by an engineering contractor (EC), typically with responsibility for design, procurement, construction and installation the facility. The client's requirements are managed and executed by the EC, including recording costs during this phase. During the operations phase, the costs incurred are recorded by the user/owner.

The cumulative committed life cycle cost curve increases the fastest during the acquisition phase, where it can be said that about 80% of the costs are 'commitments' by the decisions made during earlier processes in this phase e.g. concepts and design.

The cumulative life cycle cost curve shows that even though 80% of the costs are committed, only about 20% of the costs are actual costs, which implies that 80% of the actual costs are incurred during the operation phase.

The potential for life cycle cost savings therefore diminishes from the project to the operations phase. The manner in which companies try to affect these costs early in the acquisition phase is to specify technical requirements to ensure that the product will deliver to expectations over the life-cycle.

1.5 Rationale for the Study

Of the process equipment used at petrochemical facilities, process columns tend to be of the largest in terms of initial capital cost. These vessels dictate the energy and mass balances and the use of various pieces of auxiliary equipment (e.g. re-boilers, pumps, condensers, drums, instrumentation) in process plants. Thus the design and construction of a process vessel encompasses more than just the vessel itself. It was for this reason that process columns was chosen as the equipment for investigation in this research. The process columns were all within the SASOL Synfuels Secunda Refinery area.

The rationale regarding technical specifications was to identify high quality SASOL specifications directly related to the technical integrity of vessels. These specifications were ranked by a group of engineers from the SASOL Technology Mechanical and Metallurgical department. This department is responsible for the generation of user requirements in the form of specifications. The results from the ranking would be compared to failure history in the chemical process industry.

The last source of information used in the study was based on actual vessel history for the process columns in the Synfuels complex. The history includes failure and repair history as well as the associated costs recorded by the business unit for the process columns.

1.6 Report Structure

The structure of the research as documented in this report is based on three main sections:-

i) Theoretical Framework
ii) Data Gathering
iii) Data Analysis

The theoretical basis of the report outlines the sources of literature that was used to develop a framework for the research study. The theory merges the fields of mechanical engineering in terms of pressure vessel design and asset management in terms of life-cycle costing.

The data gathering section addresses the methods used to collect the data relevant to the research, within the context of the SASOL plants and facilities investigated. The integrity of the data was dependent on the quality of the documentation records kept at SASOL. The data comprises of information extracted from the SASOL specifications, respondent opinion, historical vessel information, as well as costing data for selected columns.

2 LITERATURE REVIEW AND THEORY

This research combines engineering and technical specifications, user requirements and life-cycle costing for pressure vessels and the literature review is focused on these topics.

2.1 Factors Considered in the Design of Process Columns

The mechanical design of a pressure vessel is governed by the process need for the column. Process columns are generally used as separation equipment exploiting either distillation or absorption processes. Once the process has been decided upon, the important issue is to design the column or vessel to satisfy the corresponding requirements.

2.1.1 Column Height

The process application dictates the height and diameter of the vessel. These dimensions are important for the mechanical design of the vessel since the geometry affects the adiabatic and hydraulic efficiency of a column. The method discussed in this section is one used by Ulrich (1984:195).

The vertical column height H_a can be determined by stacking the heights, stage after stage. The required height of each stage H_t i.e actual tray separation height; will be determined by the tray supplier based on the type of tray used.

The vertical column height can therefore be given as:-

$$H_a = \frac{N \cdot H_t}{\epsilon_s}$$

where,

ϵ_s - overall tray efficiency

N - number of trays

H – required height of each stage

2.2 Design Codes of Construction

Codes of construction take into account the safe design of vessels. Design codes are based on material stresses depending on the stress theory used to formulate the code, the formulas adopted by the code will indicate a minimum thickness for a particular material for its stressed state. This will be the minimum required thickness to contain the pressure at a corresponding temperature, under specified process conditions.

The allowable stress values for the material and the corresponding stress formulas therefore directly dictate the thickness of a vessel. In terms of process columns, as little as two or three millimetres could drastically impact on the weight, and therefore cost of the column.

Codes of design and construction are not prescriptive on material selection based on process medium; they are based on allowable stress values for pressure and temperature ratings. It is ultimately the user that selects the vessel material based on the characteristics of the process. As a crude example, you could decide to use either carbon steel or stainless steel in the construction of a process column where the process is fairly corrosive. On the one hand you could pay less for a carbon steel vessel that will need replacement after a number of years (once the vessel has corroded below its minimum required design thickness). On the other hand you could have a much higher initial capital cost to purchase a stainless steel column, which would not corrode due to the material properties of stainless steel. This choice however is not code prescriptive, but lies with the user.

The rate of corrosion for different vessel materials, and the same process medium, will vary based on the material properties in reaction to the process. A vessel material that corrodes within months of operation in a specific process medium is obviously an incorrect material selection. The user could however select a material with a corrosion rate that will span two or three years and accept, at the time of material selection, that the vessel will require maintenance and repair to restore the material requirements. Another approach would be for the user to build in extra material to account for the corrosion upfront in the form of a corrosion allowance in the material thickness. The user could also decide to use a corrosion resistant material for the application and so doing negate the effects of corrosion and any future maintenance costs related to corrosion.

It is therefore the user's prerogative, in terms of the life cycle cost of the vessel, to determine whether to account for these costs during the acquisition of the vessel or over the operating life.

2.3 Technical Project Specifications during the Project Phase

Martin (1997:211) defines a specification as "*A document intended primarily for use in procurement, which early and accurately describes the essential technical requirements for items, materials or services including the procedures by which it will be determined that the requirements have been met*". As defined by the American Department of Defence standard MIL-STD-961; the specification investigated in this research is the Product Specification.

Technical specifications are used to ensure that user specific requirements are incorporated into the design and fabrication of pressure vessels. These user requirements are based on industry best practice, operating experience and design optimisation over years of continuous improvement. Because of this, user requirements in the form of specifications are the intellectual property of the user and are usually not open for review or use externally.

2.4 Pressure Vessel Failures and Defects

The stored energy contained in pressurised systems dictates the inherent threat of a damaging failure. Failures of pressurised systems are very costly, and can range from catastrophic damage to superficial repairs [29].

Mathews [17] defines failure as *a general term to imply that a part in service (1) has become completely inoperable, (2) is still operable but is incapable of satisfactorily performing its intended function, or (3) has deteriorated seriously, to the point that it has become unreliable or unsafe for continued use.*

In Lee's Loss Prevention in the Process Industries Handbook cited in [16], a survey done by Phillips and Warwick for defects in pressure vessels built to high standards is referenced. The following section outlines the results of the Phillips and Warwick data.

Failures of pressure vessels may be broadly categorised as catastrophic failures and potentially dangerous failures according to the survey of Phillips and Warwick in Table 1, showing that in-service related failures occur more frequently than failures during vessel construction.

Table 1: Pressure Vessel Failure Categories [16]

	Sample Size	*Failure Rate* (failures/year)	
		Potentially dangerous	*Catastrophic*
Failure in construction	12,700 vessels	5.5×10^{-4}	2.3×10^{-4}
Failure in service	100,300 vessel-yrs	1.25×10^{-3}	0.7×10^{-4}

Phillips and Warwick classified the causes for the in service failures and this can be seen in Table 2.

Table 2: Causes and Methods of Detection of Service Failure in Pressure Vessels [16]

	No. of Cases	*% of total Cases*
Causes of failures:		
Cracks	118	89.3
Maloperation	8	6.1
Pre-existing from manufacture	3	2.3
Corrosion	2	1.5
Creep	1	0.8
	132	100.0
Causes of cracks:		
Fatigue	47	35.6
Corrosion	24	18.2
Pre-existing from manufacture	10	7.6
Miscellaneous	2	1.5
Not ascertained	35	26.5
	118	89.4
Method of detection:		
Visual examination	75	56.9
Leakage	38	28.8
Non-destructive testing	10	7.5
Hydraulic tests	2	1.5
Catastrophic failure	7	5.3
	132	100.0

From the data it can be seen that about 89.3% of pressure vessel failures may be attributed to cracks caused by fatigue at 35.6% of the cases. Further to this, Phillips and Warwick recorded the reasons for seven catastrophic failures, they were i) maloperation (four cases), ii) fatigue (two cases), and iii) pre-existing from manufacture (one case).

From the data collected by Phillips and Warwick it is observed that the major cause of failure during the vessel's service life can be attributed to cracks and further to that the cause of the cracks resulted from fatigue. In the cases for catastrophic failure, fatigue was again listed after maloperation as a reason for failure.

2.5 Economics of the Design and Construction of Process Columns

The intent is to look at Total Cost of Ownership (TCO) *(Amadi-Echendu)*

Total Cost of Ownership = acquisition + operation and maintenance costs over the useful (economic) life of the vessel.

With large capital projects the convention is usually to minimise the acquisition costs such that operation and maintenance costs are underestimated and sometimes taken for granted.

Acquisition costs are governed by the design of the process column. The costs for a column can be divided into three major components viz. i) the cost of the shell, which includes heads, skirts, nozzles and manholes and ii) the cost of internals including trays, packing, distribution systems, supports and compartment separation and iii) external attachments like ladders and platforms, handrails and insulation. The acquisition cost of a process column is usually estimated based on the weight of the column (determined from the diameter and height of the vessel, which is calculated based on the process design) (Peters and Timmerhaus (1991: 792)). The thickness of the vessel shell is based on the mechanical design of the vessel and is based on either the design pressure and temperature of the vessel, or an alternate design case like wind loading, pressure testing, or seismic loading.

The operating and maintenance costs of a vessel are in most cases higher than the initial cost of acquiring the vessel. The operating and maintenance costs are difficult to quantify at the time that decisions are made regarding user requirements for technical specifications that have long term implications on TCO and so the ramifications are difficult to justify.

Factors affecting high operating and maintenance costs can be attributed to:-

i) wages for manpower is a cost that constantly increases with time

ii) downtime, this is a source for major losses, and in the petrochemical industry, downtime, outside of planned shutdowns, can account for high operating losses.

2.6 Economic Consideration and Cost Reduction

The design trend is to use large sections of vessels in an attempt to reduce capital costs by eliminating duplicity of auxiliary equipment, controls and utilities. The major cost associated with a pressure vessel is the material cost. Reduction of the material weight, at a given range of allowable stress, results in a lower acquisition cost for the application. Acquisition costs are therefore directly related to the choice of materials for design, fabrication and construction of vessels.

2.6.1 Engineering Design

Many different design and construction codes exist, and it is imperative that procedures and specifications exist to aid the designer in determining the design of the vessel using the most appropriate design code (Harvey 1978:430).

The direct cost associated with engineering design arises from the time it takes to obtain and apply requisite knowledge and know-how to obtain the optimum solution to user requirements.

Technical specifications exist to ensure that user requirements that may derive from industry best practice and experience are applied when acquiring new vessels. The same applies in terms of knowing and understanding the specification and the application thereof. A new or junior engineer will take longer to gain experience and knowledge of the specification and it will take time for the engineer to apply the specification in a way that ensures an optimum result.

2.6.2 Materials of Construction

Material Selection

There is paramount emphasis on safety in the design and construction of pressure vessels. From 20 March 1905, where a boiler explosion at a shoe factory in Massachusetts resulted in the deaths of 58 people and injuries of 117, the rules and regulations that govern the design and construction of pressure vessels have constantly been improved to ensure the safety of the environments where a pressure vessel is operated (Chuse 1993:1).

Similarly, the technology used to manufacture and test materials have improved and detailed information on how a material is expected to react in stressed conditions is now readily available.

The code(s) selected for the design and construction of a process column will have a list of materials that have been tested and approved for use in fabrication. The listed materials will have taken into account various mechanical and metallurgical properties for the material i.e. tensile strength, yield strength, elongation, reduction in area etc. Safety is therefore inherent in the design code of construction.

The cost of a material is usually driven from the project management function and the fact that the process application of the column needs to make business sense. A titanium process column could withstand some of the most aggressive process streams, but it does not make business sense to fabricate in this very expensive material if the process only requires carbon steel. Material selection is based on both the endogenous and exogenous process conditions.

Procurement of columns

The procurement of process columns can occur as part of i) a large capital project in which the columns form part of the process for a new plant; or ii) as a replacement column for part of an existing plant. In the latter, the process data is easily available for the selection of the material. When selecting material for a new process plant, unless the process is tested and proven, the process data available at the time of ordering the column might not be accurate in terms of material selection. The smallest percentage change in process conditions, for example, in the amount of trace elements of acids could severely impact on the metallurgical properties of the vessel.

Material Costs

Material costs account for 50 to 60 per cent of the total column costs, so in order to reduce costs for process columns; material is targeted as the major component to cut costs (Harvey 1978:431).

2.6.3 Method of Fabrication

After raw material cost, fabrication cost accounts for the bulk of the initial capital cost of a process column. Improvements in welding technology, specifically, have a direct impact on the initial cost a vessel (Harvey (1978:442-457)).

Not only has welding technology revolutionized the joining of pressure plates, by moving from riveted construction to welded construction. But advancements in the technology of welding have moved from manual welding to automated welding, making the welding of large columns possible. Further to this, automated welding has greatly reduced the time taken to construct vessel components. This reduction in schedule, in most cases, is a positive driver on projects, and fabrication could indirectly contribute a large portion in the reduction of costs in terms of opportunity costs for start-up.

Process columns are usually the long lead items on projects and they have a direct impact on the schedule and start-up of the unit.

The fabrication of process columns is a focal point in terms of maintaining or reducing schedule.

According to Harvey [1978], fabrication accounts for approximately 35% of the total vessel cost. This is primarily due to the joining of pressure parts. The opportunity to reduce costs during fabrication therefore should be targeted at 1) eliminating joints and 2) using economical methods of fabrication.

2.7 Life Cycle Costing (LCC) for Process Columns

The life cycle cost of a process column is sum of all costs incurred during the life time of the process column i.e. total procurement and ownership costs (Dhillon 1989:3). The following section details various aspects of LCC.

2.7.1 Considerations for LCC

Factors like the source of fabrication, materials, price fluctuations, and company policies play a major role in the decision for the economic design and construction of a vessel (Peters and Timmerhaus (2004:230)).

Source of fabrication plays an important role when standard types of equipment are considered. This typically includes tanks, pumps and coolers. The fact that these pieces of equipment have a standard design and construction means a remarkable reduction in price. Generally, process columns are uniquely designed pieces of equipment requiring specific design and construction and therefore independent quotation.

When considering materials, an example would be that carbon steel is cheaper than stainless steel by a fair margin. If the demand for carbon steel in the international market suddenly increased steeply, lead times for the material as well as prices will quickly rise. This often means that the alternative, stainless steel, would become a viable option. This consideration is of importance during the acquisition phase of the life cycle.

Price fluctuations in the marketplace for process column fabrication play a role in the economic consideration. Wage and labour rates directly affect the fabrication costs of these pieces of equipment and so fluctuations could occur widely from one period to the next.

Company policies would include strategies in terms of safety and design, and stringent safety requirements have a direct impact on the costs of a process column. Company specific specification requirements affect the initial capital costs of process columns. The level of detail and applicability of technical specifications as part of the fabrication of the column therefore needs to be part of the economic consideration at this stage of the project.

All of the factors mentioned above have a direct economic effect on the initial capital cost of process columns.

2.7.2 Life Cycle Cost Categories

The initial capital cost of a process column forms one of many costs that a process column would incur over its life cycle. This section outlines the major categories into which the costs can be grouped (Dell'Isola (2003:xiii – xxiv)).

The categories of costs as defined and listed by Dell'Isola (2003: xx) can be summarised as follows:-

i) Initial Costs
   1. Construction
   2. Fees
   3. Other

ii) Future Facility One-time Costs
   1. Replacements
   2. Alterations

3. Salvage
4. Other

iii) Future Facility Annual Costs

1. Operations
2. Maintenance
3. Financing
4. Taxes
5. Insurance
6. Security
7. Other

iv) Functional Use Costs

1. Staffing
2. Materials
3. Denial of Use/ Lost Production Costs
4. Other

It is important to note that when costs are compared for process columns over their life cycle, the costs are not duplicated, but that they are identified and then categorised to avoid accounting for the cost more than once.

Initial costs would typically include the costs associated with the design and manufacture of a process column. This is the initial capital cost of the process column, and would usually include the cost of using technical specifications in the purchase price of the column. Besides this cost, it also takes into account the initial costs for transportation to site, inspection and erection, in other words, the total installed cost for a process column.

Future facility one-time costs are the major costs that are incurred, not annually, but randomly over the lifetime of the process column. The costs typically include replacement, large scale refurbishment or salvage costs. These costs typically do not get repeated.

Facility annual costs are the costs associated with the running of the process columns. These are typically operating, maintenance costs and other built environment costs.

Functional use costs are the costs associated with the operation of the column. They would typically include aspects like staffing and loss of production costs. The latter is of extreme importance, because if a process column is defective and the cause for a plant shutdown, the loss of production attributed to this loss is usually large. Another functional cost associated with columns, is that of internals. A packed process column will have higher functional costs due to the time and effort it takes to change out packing as opposed to trays. One, more specific process column type, is that of catalytic distillation, which required the turnaround of the catalyst inside the column. This is a functional cost that would have a greater impact than that of a conventional distillation column.

The costs, for the purposes of this research, lie within costs associated with technical specifications, the categories that will be focussed on are the costs associated with the column directly i.e. initial equipment cost, maintenance costs, replacement costs etc. as it will not be of any value to analyse staffing, operations or fees costs for the intents of this research.

2.7.3 Economic Evaluation

For the costs, as categorised, to be compared in an economic evaluation, the evaluation needs to take into account the time at which the cost was incurred. This is achieved by expressing all costs as equivalent costs at the same baseline and using a "time value of money" approach which takes into account the changing value that money has over time (B.S. Dhillon (1989 – xxiv)).

The current value of a sum of money will not have the same value as that of the same sum of money a year later. Also, the future value of a sum of money will have a higher value due to interest, the effects of inflation also need to be considered and so, a present sum of money also has less value as time progresses due to the effects of inflation.

To take these factors into account, the concept of interest is important to understand. Interest takes two forms viz. simple interest or compound interest.

For simple interest, interest is only paid on the original sum of money and it does not accrue based on interest. The formula used for this calculation is:-

$$T = P(i) \cdot (n)$$

where: T = Total interest
P = Principal amount
i = Interest rate
n = Interest period

For compound interest, interest earned for an interest period is added to the principal amount. Interest for the next period is then earned on the principal amount plus the interest for the first period. Interest is therefore earned on interest and hence compounded.

The basic economic formula for compound interest is:-

$$F = P \cdot (1 + i)^N$$

or

$$P = \frac{F}{(1 + i)^N}$$

where:

F	-	Future Value
P	-	Present Value
N	-	Analysis Period
i	-	Interest Rate

The Net Present Value (NPV) of the cash flows for a period (N) can be expressed as the sum of the present values for the cash flows over the period. This can be expressed mathematically as:

$$NPV = \sum PV = \sum_{N=0}^{N=k} \frac{F}{(1+i)^N}$$

In the same way that interest is considered over time, depreciation needs to be considered over time. The decline in value of engineering equipment can be attributed to the following factors:-

- i) functional depreciation
- ii) technological depreciation
- iii) physical depreciation
- iv) monetary depreciation

Functional depreciation is explained as a change in demand or service of equipment. For example, a petrochemical process could be changed or altered to distil different products though an existing process column by altering the internals. A change in feed to a column could also affect the functionality of a column and in turn the value of the column.

Technological depreciation occurs as newer technologies emerge in industry and replace older outdated technologies. This is very evident in tray and packing technology used for internal in process columns. As new try designs become available, to separate streams more sharply, older types of trays devalue and become obsolete. As technology progresses the older equipment technology and design becomes uneconomical and therefore devalued.

Physical depreciation is as a result of the physical degradation of the equipment. As a piece of equipment ages, its ability to perform its initial function decreases as it physically degrades.

Monetary depreciation is as a result the change in the buying power of money initially used to purchase a piece of equipment.

2.7.4 Quality Versus Cost

When quality is considered for pressure vessels over its life cycle, the term *technical integrity* needs to be defined.

Technical integrity is defined as:-

"The assurance that, under specified operating conditions, there is no foreseeable risk of equipment failure that will endanger the safety of personnel, the environment, or adversely affect the business value of an asset"(Amadi-Echendu, 2003)

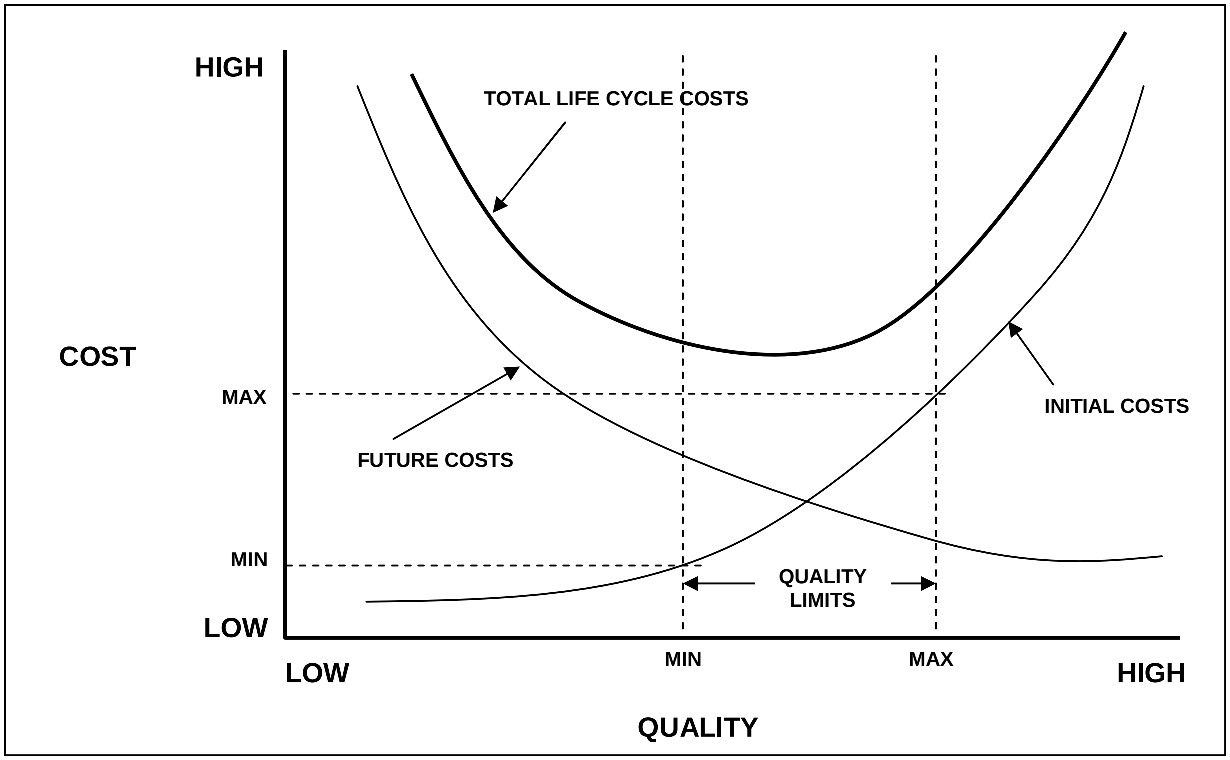
Thus when considering the quality of a vessel over its life cycle, technical integrity will be key to quality.

The intent of LCC is to compare two alternatives at the same baseline/timeline for costs over the life cycle of the process column. What this equates to for this research is that two cost alternatives are compared at the same point in time.

The first alternative being that you have a low level of upfront specification for technical requirements. This usually gives a sense of "no requirements" or "lower quality/technical integrity" equating to "lower initial cost". This usually also implies higher future costs.

The second alternative is the detailed upfront specification of technical requirements. This implies a sense of "detailed requirements" or "higher quality/technical integrity" equating to higher initial cost and by implication lower future costs.

This scenario is illustrated in Figure 6 below.



Source: Dell'Isola et al (2003:xxiii)

Figure 6: Relationship between Cost and Quality

2.8 Literature Review Overview

The dimensions of process column are governed by the process design of the column. The codes of construction dictate the vessel wall thickness based on design consideration for internal and external pressure, wind loading, seismic design etc. The combination of height, diameter and shell thickness will therefore determine the major initial capital cost of the process column based on mainly on weight. User requirements in the form of specifications, applied over and above codes and standards, will have associated initial capital costs. When considering where most failures in the process industry occur, the Phillips and Warwick data indicates that most failures are caused by cracks with the majority originating from fatigue. When considering all the costs associated with process columns over its life cycle, consideration to the impact of specifying a requirement upfront needs to be considered when the total cost of ownership of the vessel is considered.

3 RESEARCH STRATEGY AND METHOD

3.1 Problem Statement

Specifications, over and above design codes and statutory requirements, (during the project phase) are applied with the intent that process vessels are acquired, installed, and commissioned for operational use. The trade-offs between user requirements, technical specifications and operating conditions take place in the early phases of the project, and these translate into ownership costs during the operations phase. It thus begs to question how much should be specified apriori to achieve minimal costs of ownership over the useful life of a vessel. The problem is therefore to determine whether technical specifications have an impact on the total cost of ownership of process vessels.

3.2 Research Objectives

v. *To examine technical specifications for pressure vessels based in user perceptions.*
vi. *To identify from historical data, the failure modes of process vessels in practice and to relate the failure modes to design and construction specifications.*
vii. *To analyse the costs recorded for the process columns chosen as part of the investigation.*
viii. *To establish the impact of project technical specifications on the total life cycle costs of pressure vessels*

3.3 Research Questions

i) *Are there similarities between the failure history available for the general process industry and the technical specifications ranked by SASOL respondents?*

ii) Are there similarities between failure history of process columns in the SASOL sample and the technical specifications ranked by SASOL respondents?

iii) Do technical specifications impact the total life cycle costs of process columns in the SASOL sample?

3.4 Research Method

The study is based on SASOL technical specifications for process vessels, as well as actual columns in use in petrochemical refinement or production. The results will therefore be limited to this type of equipment.

The research methods include:-

i) A Delphi survey on SASOL technical specifications
ii) Primary data from historical defects/repair records
iii) Primary data from historical cost records

3.5 SASOL Specifications

The SASOL technical specifications are not written in a way that LCC requirements are easily identified. The first leg of the research was therefore aimed at extracting the technical specifications that related to the LCC of process columns.

A list of specifications was identified for detail requirements to be extracted from. These requirements would be the basis for the questionnaire.

The list of the hierarchy of specifications can be seen in table 3.

Table 3: SASOL Pressure Vessel Specifications

Pressure Vessel Specifications
1. Mandatory Requirements for Boilers, Pressure Vessels, and Portable Gas Containers 2. Pressure Vessels Categories 1, 2 and 3 3. Pressure Vessels – Supplement for Carbon and Low Alloy Steels 4. Pressure Vessels – Supplement for Austenitic and High Alloy Steels 5. Pressure Vessels – Supplement for Alloy Clad and Alloy Lined Steel 6. Pressure Vessels Supplement for Slender Vertical Vessels 7. Pressure Vessels Supplement for Severe Services 8. Pressure Vessels Category 4 9. Vessel Trays – General 10. Welding of Pressure Vessels : Categories 1, 2 and 3 11. Pressure Equipment 12. Heat Treatment 13. Selection of Materials for Low Temperature Service 14. Mechanical Engineering Requirements – Specification Clarifications and Amplifications

A Delphi approach was taken to obtain user perceptions of the technical specifications. The specifications were ranked according to the opinion of SASOL respondents on the specifications affecting the technical integrity of pressure vessels.

The respondents for the questionnaire were taken from the SASOL Technology Mechanical and Metallurgical division. This division is responsible for the generation of mechanical technical specifications in the SASOL group of companies.

3.6 Historical Defects/|Repair Data Captured

The second leg of the research was data gathering based on the historical information available for process columns in the SASOL Synfuels complex. Historical data based on plant records of defects / repairs are recorded in the inspection archives of the complex. The records for defects / repairs are based on metallurgical investigation. The metallurgical contractor to SASOL records all reports issued to SASOL and these reports were used as the basis for data collection. The data spans as far back as the original construction of the Synfuels site in the late 1970's.

Because of the size of the Synfuels complex, a refinement in process column sample size was needed. The Synfuels site ranges from the gasification of coal all the way through to the refinery at the end of the process. The complex is sub-divided into business units responsible for various processes. Process columns are not found in all business units since some units are responsible for feedstock coal preparation and others for utilities like steam and air.

The refinery business unit was therefore selected because it comprises of a number of processing plants that refine chemical and petroleum products from various sources in the Synfuels complex. In addition, refining by definition, indicates that feed is cut into various product streams, using process columns, albeit distillation, absorption or washing/stripping. The various processing streams in the refinery business make it a unit with diverse selection of materials of construction for vessels.

The metallurgical reports on the process columns were the first point of data capture; the reason being that the catastrophic failure of a process column is highly unlikely based on design in accordance with the Occupational Health and Safety Act of South Africa.

One of the main reasons process columns do not catastrophically fail in operation is that the material of construction and its welding is tested at the fabricators works to a stressed state higher than any stressed state the material will see during operation. Any defect in the material, or the welding of the material will therefore be evident during the pressure testing of the vessel.

Failure, for the purposes of this research, therefore is not catastrophic failure (due to design), but rather *failure of materials or the ability to optimise requirements to prevent re-occurrence of weak design for constructability or maintainability*. This can also be stated as a defect that requires rectification work to enable the vessel to meet the design intent.

3.7 Historical Cost Data Captured

The third leg costing section of the research was based on historical costs for the process columns within the scope of the selected refinery business unit.

The costs considered for a full Life Cycle Costing assessment would include all costs as per the cost categories outlined in § 2.7.2. For the purposes of this research the method for cost analysis is limited to the costs that arise from defects/failures recorded during inspection or operation.

From the historical database of the defects and repairs on columns, data was generated, and filtered for defects affecting *technical* as described in § 2.7.4. Associated costs for the defects/repairs were then extracted. These costs represent actual costs incurred at a specific time during the life of the process column. Using the time value of money calculations, the costs are compared to the initial cost of procuring a vessel.

4 DATA GATHERING

4.1 Description of Sample

Data related to process columns was collected from twenty three processing units within the refinery business unit as shown in Table 4. Nine of the units are identical within the SASOL West factory and the SASOL East factory.

Table 4: Tabulation of Columns per Refinery Unit

Unit	No. of Columns
014	4
214	4
015	2
215	2
027	1
228	0
029	6
229	4
030	3
230	3
031	0
231	0
032	9
232	9
033	2
233	2
034	1
234	1
035	8
235	7
078	4
079	4
090	2

4.2 Questionnaire

The SASOL specifications are grouped according to the type of process equipment that is purchased. So there would typically be a specification for reciprocating pumps, tanks and heat exchangers. There is no particular specification for process columns, since the design of the pressure envelope would fall within the specification for pressure vessels. This specification would contain the user's requirements for design and fabrication of the vessel.

The pressure vessel specifications do not explicitly state which requirements are related to life cycle costs.

The questionnaire is intended to not only extract specification parameters relating to life cycle cost, but also to identify user requirements that have a direct impact on vessel integrity.

These requirements were then refined to contain only those affecting the ***technical integrity*** of a process column. Technical integrity is defined as:-

"The assurance that, under specified operating conditions, there is no foreseeable risk of equipment failure that will endanger the safety of personnel, the environment, or adversely affect the business value of an asset"(Amadi-Echendu, 2003)

Technical specifications were analysed based on vessel integrity, and these were then listed as the areas that would be addressed by the questionnaire.

The aim of the questionnaire was to determine what SASOL respondent opinion was in terms of vessel integrity. The various requirements were listed and the respondent asked to rate the technical specification in terms of effect on vessel integrity.

These specifications were then ranked in terms of those having extreme effect on technical requirements to those having little or no effect on technical integrity.

The aim was to determine the link between these specifications, and the actual vessel defects.

4.2.1 Design

The questionnaire was divided into three sections i) Design and constructability specifications ii) Material selection and quality specifications iii) Welding specifications, these being the areas that would largely affect the integrity of a vessel during design and construction.

The questionnaire was presented at a SASOL Technology training day together with background to the research that was being done; the presentation can be viewed in Appendix A. The number of participants at the training day was forty-two.

The participant was then asked to rate the specification requirement in terms of impact on technical integrity.

The questionnaire can be viewed in Appendix B.

4.2.2 Section 1: Respondent Profile

This section was crucial to obtaining a profile of the respondents for the survey. SASOL Technology comprises of young engineers and experienced industry experts, it was therefore important to determine the level of expertise of the respondent in his/her completion of the questionnaire. The *designation/responsibility* within the department was therefore necessary for respondent profiling.

The division in which the respondent worked was also important since the questionnaire was divided into three distinct sections i.e.

i) design and constructability,
ii) materials and quality and
iii) welding

The *number of years of SASOL experience* was relevant to the weighting the respondents' rating. For example, an engineer with fifteen years SASOL experience would have working knowledge to support his/her opinion.

4.2.3 Section 2: Design and Constructability Specifications

This section deals with the background of the chosen design specifications, all of which affect the technical integrity of process columns. The detail can be viewed in Appendix C.

4.2.4 Section 3: Material Selection and Quality Specifications

This section deals with the background of the chosen material and quality specifications, all of which affect the technical integrity of process columns. The detail can be viewed in Appendix C.

4.2.5 Section 4: Welding Technical Specifications

This section deals with the background of the chosen welding specifications, all of which affect the technical integrity of process columns. The detail can be viewed in Appendix C.

4.3 Metallurgical Reports and Vessel Repairs

SASOL Synfuels, a processing facility, is sub-divided into various business units. The Refinery comprises of many processing streams as well as a variety of processes with numerous process columns.

Three sources of information regarding the history of the columns exist within the SASOL systems. They are:-

i) Inspection Files

ii) Recommended Repairs

iii) Metallurgical Reports

The inspection archives contain information for all the equipment on site. The inspection files are a history report file on the inspection activities carried out on a vessel since its commissioning on site. The report is updated at every inspection, usually on a frequency of four years.

The recommended repair documentation, also housed in the archives, is a form completed after inspection is carried out, and inspector recommends a vessel repair based on his/her inspection findings. The area leader for the unit has the option of repairing or not, depending on information he obtains from a vessel design office. The recommended repair therefore does not confirm that work was executed to rectify a defect.

The metallurgical reports are housed within the business units as well as originals kept at the metallurgical consultants, a contractor to SASOL i.e. SECMET. These are reports requested by the units as an investigation into material problems experienced on site.

4.4 Life Cycle Costing Data

The costs associated with defects/repairs were based on the costs recorded by SASOL for the columns. Two problems arose from the effort to obtain costing information on the process columns for the refinery units.

The first challenge was the on the age of unit. The plants (east and west) were built in the early 1980's. The methods and usefulness for costing information regarding all aspects of a process column was not clear in the 1980's so only major costs were recorded. Further to this, there were periods where no information was kept and the description of costs were not recorded in a way that is useful for the purposes of this research.

The second challenge was that of the systems employed to record costing data. In the initial stages of the column's life cycle, paper was the method of record for costing data. This was then followed by a MIMS system that accounts for the largest part of the costing history for the process columns in the refinery area.

The MIMS system was followed by SAP and the transfer of information from MIMS to the SAP system left holes in the information captured prior to 2001. SAP now houses more pertinent costs for the process columns, but only dates back to 2001. All information prior to that was obtained from the older MIMS database, but the quality of the data was questionable.

For the reasons mentioned above, it was decided that the columns with the costing data that was most complete would be analysed as part of this research.

5 DATA ANALYSIS AND DISCUSSION

The data analysis is divided into three sections based on the research strategy. The first section analyses the data gathered as part of the respondent opinion, in the form of the results of the questionnaire "the impact that specification requirements have on technical integrity of process vessels".

The second section analyses the data obtained from historical data reports for process columns on the SASOL Synfuels refinery, and the third section is based on recorded cost data captured for the process columns.

5.1 Questionnaire Data analysis

The analysis type selected to evaluate the results of the questionnaire was a weighted evaluation technique. The method was chosen due to the profile of the participants. The questionnaire was handed to young engineers who had just joined the SASOL Technology Mechanical and Metallurgical engineering department, as well as Chief engineers who have been working at SASOL since the construction of the plant in the 1980's.

Because of this, a preferentially weighted score for an engineer with years of experience would contribute more to the overall rating for a question than the score of a less experienced engineer.

The weighted evaluation tables can be viewed in Appendix E. The method used was a ranking of the engineers in the department. A preference table was set up and engineers would be ranked against each other. The approach was that years of experience would to determine preferential weight of one engineer, against another.

Another filter that was the applicability of the engineer's background to the section he/she was evaluating. The SASOL Technology group is divided into functions and support groups. Some engineers are detailed pressure vessel specialists, where others work as support engineers on three categories of projects i.e. i) existing plant optimisation and modification, ii) small projects, iii) large capital projects. The exposure of the engineer's work is therefore important in the preferential weighting of his/her score. For example, a pressure vessel specialist will have more background in using ASME VIII Div1 as a design code, than an engineer working on plant optimisation that consists mostly of piping design.

Further to the weighted analysis, a graph for the average score for each of the questions was plotted to cross reference the trend between the weighted evaluation and the actual scores given by the respondents. The output was used to ensure that the trend seen in the weighted evaluation is based on the average scores by the participants, reason being that a ***no comment*** column was allowed in the questionnaire. The scoring for this column would be 0, and if the majority of the respondents had no comment on a technical specification, but the few respondents that knew of the specification rated it as having an extreme effect on technical integrity, the overall weighted score could still reflect as being low.

The second plot of average score is therefore used as a verification of score tool in this research to ensure that the results are interpreted correctly. As can be seen in paragraphs 5.1.2 to 5.1.4, there is a close match of the trend between the results of the weighted evaluation and the average scores.

5.1.1 Section 1 – Participant Profile

Of the forty-two participants, twenty had responded by completing the questionnaire giving a response rate of 47.6%. The data captured from the questionnaire can be viewed in Appendix D. This section deals with the analysis of the questionnaire results.

Figure 7 shows, as a percentage, the composition of the participants in terms of job level.

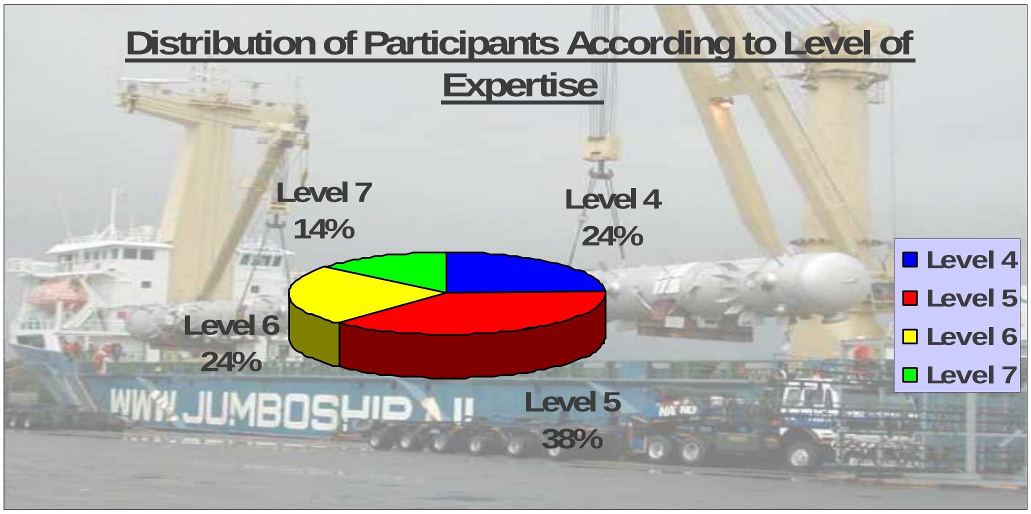


Figure 7: Distribution of Participants According to Level of Expertise

The distribution is very representative of engineers in the department. The following are definitions of job levels at SASOL Technology Mechanical and Metallurgical Engineering:-

i) Level 4 – Principal Mechanical Engineer
ii) Level 5 – Senior Mechanical Engineer
iii) Level 6 – Mechanical Engineer
iv) Level 7 – Assistant Mechanical Engineer

As can be seen in the distribution, the questionnaire was handed to a representative range of engineers. In the majority were senior engineers, followed by principal engineers and engineers.

From the respondents to the questionnaire, the distribution is shown in Figure 8 below.

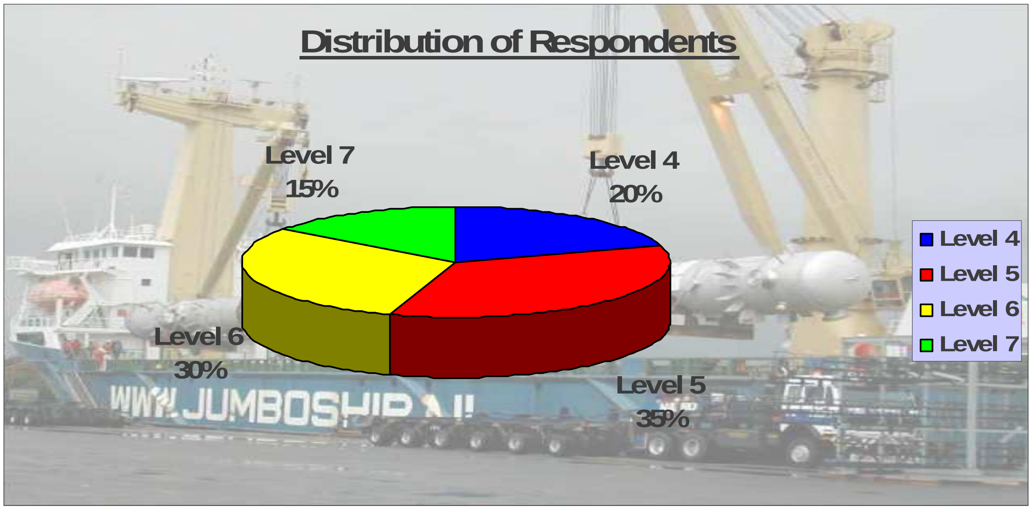


Figure 8: Distribution of Respondents

As can be seen, the distribution of engineers that responded to the questionnaire is comparable with the distribution of the engineers that the questionnaire was handed to.

What is also important to note is that a significant number of the level 5 senior engineers are responsible for writing specifications within SASOL, with review and approval by the level 4 principal engineers. The philosophy and responsibility for specifications lies mostly with the principal and senior engineers.

5.1.2 Section 2 - Design and Constructability Specifications

The method used to analyse the results for the questionnaire was a weighted evaluation.

Sections 2, 3, and 4 was based on rankings of the specification requirements in terms of how much the respondent sees the requirement affecting vessel technical integrity.

The rankings were as follows:

Ranking of 5 - Has an ***extreme*** affect on vessel technical integrity

Ranking of 4 - Has an ***important*** affect on vessel technical integrity

Ranking of 3 - Has ***somewhat*** of an affect on vessel technical integrity

Ranking of 2 - Has ***little*** affect on vessel technical integrity

Ranking of 1 - ***Does not*** affect on vessel technical integrity

Ranking of 0 - Not within my field of expertise

The following section discusses the results of the respondent feedbacks for Section 2 of the questionnaire viz. Design and Constructability Specifications. Appendix C describes each specification in detail and the specifications that were ranked can be viewed in table 5 below.

Table 5: Table of Design and Constructability Specifications

	SPECIFICATION REQUIREMENT
1.	The use of the ASME Code to design columns as opposed to other codes of construction
2.	The use of ASME VIII Div 1 as opposed to ASME VIII Div 2 for design
3.	Standard tabulated piping loads applied to vessel nozzles (tabulated values)
4.	The use of 2:1 semi-ellipsoidal heads
5.	Torispherical heads NOT being allowed on columns with an L/D ratio equal to or greater than 10
6.	The use of hemispherical heads of crown plate and petal design
7.	Permanent internal/external attachments NOT allowed on knuckle areas of heads
8.	Nozzle attachment to shell weld to be full penetration through neck to outside of shell for nozzles 3" larger
9.	SASOL Category 1 and 2 columns to have integrally reinforced nozzles
10.	Cyclic loaded vessels to have lip type forgings
11.	Bolts and nuts on nozzle flanges must be removable towards the vessel
12.	Weld build-up for skirt to head attachment weld (non-slender[1] vessels)
13.	Y-forging for skirt to head attachment (Slender vessels)
14.	Skirt to shell junction to be fatigue resistant (Slender vessels)
15.	Internal flanges to be at least B16.5 150# double welded slip-on type
16.	Column overhead structure to be drawn off the cylindrical section of the column shell instead of from the crown of the head.

[1] Slender vessel: L/D ratio greater than 12

Figure 9 is a graphical representation of the weighted evaluation of the results for Section 2 of the questionnaire. The domain of the graph is based on the questions posed to the respondent as listed in Section 2 of the questionnaire. The range for the graph was based on the total weighted score for the question by all the respondents for a specific question.

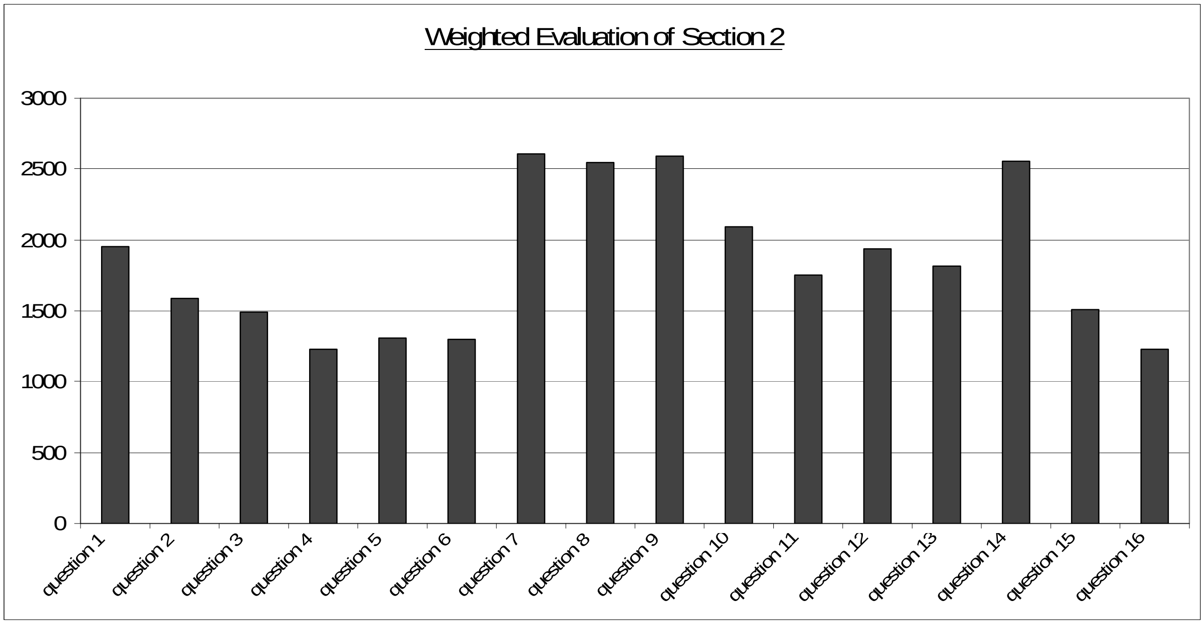


Figure 9: Weighted Evaluation of Section 2 of the Questionnaire

What can be observed from Figure 9 is that questions 7, 8, 9 and 14 have the highest weighted scores by approximately 26% higher than question 10. Based on this, it can be deduced that the respondents feel that these requirements have the greatest effect on the integrity of process columns.

Question 7 asks whether or not permanent attachments should be allowed on the knuckle areas of dished ends used for heads. This specification addresses the attachment of a component by welding to a highly stressed area of a dished end and whether it affects the integrity of a vessel.

Question 8 asks whether nozzle attachments to the shell should be full penetration welds for nozzles greater than 3 inches, and addresses the quality of the weld design when large nozzles are welded to vessels and whether this has an effect on vessel integrity.

Question 9 asks whether SASOL category one and two vessels need to have integrally reinforced nozzles, which prohibits the use of compensation pads for critical service vessels.

Question 14 asks whether the weld finish of the skirt to shell junction for slender columns affects technical integrity.

These are the specification requirements the respondents see having the greatest impact on the technical integrity of the vessel.

Of the lower scoring questions, questions 4 and 16 ranked last for the weighted scores.

Question 4 asks whether 2:1 semi-ellipsoidal heads as a preference over any other type of head affects vessel integrity. Question 16 asks whether piping the column overhead stream out of the cylindrical shell section of the column as opposed to from the top of the dished end affects vessel integrity.

The weighted average needs to be compared with the average scores for the questions. Figure 10 depicts the plot of these average score as the range and in the domain of the questions from the questionnaire.

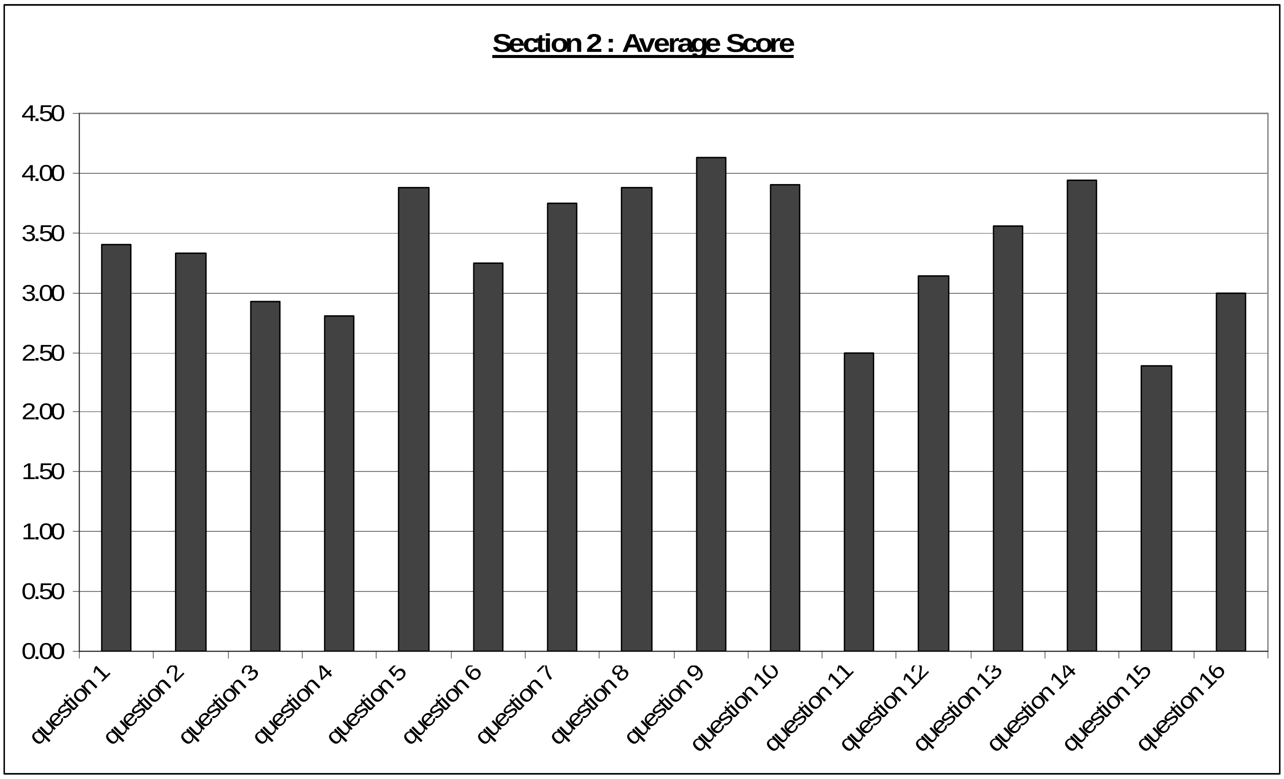


Figure 10: Average Scores for Section 2 of the Questionnaire

Figure 10 confirms the rating of questions 7, 8, 9 and 14 as the high ranking questions as seen in Figure 9. In addition, question 10 was ranked as a question having an important effect on the technical integrity of a vessel. Question 10 is with regards to using lip type forgings on vessels that are cyclically loaded.

What is also noted is that questions 11 and 15 are seen to be requirements that have little or no effect on vessel integrity. Question 11 dealing with being able to remove bolts towards the centreline of the vessel and question dealing with internal flanges.

The respondents' opinion with regards to the design and constructability specifications having a significant effect on vessel integrity can be summarised as specifications addressing weld design for nozzles and attachments to the vessel shell. The finish of the welding of the head to skirt junction was seen as a requirement having a significant effect on vessel integrity. In addition the use of lip type forgings on cyclically loaded vessels is seen to have an important impact on process columns.

5.1.3 Section 3 – Material Selection and Quality Specifications

Section 3 of the questionnaire is the section that deals with materials and quality specifications. The specifications that were ranked for this section can be viewed in table 6 below.

Table 6: Table of Material Selection and Quality Specifications

	SPECIFICATION REQUIREMENT
1.	Corrosion allowance of 3mm on carbon steel vessels if not specified otherwise
2.	Formed heads to be stress relieved
3.	Intergranular Corrosion Testing on austenitic stainless steel plate material
4.	All attachments to the shell should be of the same material specification as the shell
5.	Dissimilar materials and welds are not allowed in process services
6.	Maximum carbon content for carbon steels to be 0,25%
7.	All austenitic stainless steels to be supplied in the solution annealed condition
8.	Austenitic stainless steels in corrosive service shall be of the low carbon or stabilised grades
9.	Vessel material in Sasol Low Temperature Service (NOT Code) to be impact tested i.e. between 0^{o}C and 15^{o}C
10.	Recertification of base material (pre-fabricated parts) if hot formed
11.	UT of base material (pre-fabricated parts) both hot and cold formed if fibre elongation exceeds 5%
12.	3.1 C certification for custom made forgings
13.	Intermediate Stress Relieving for carbon steel components with fibre elongation > 5% and stainless steel with FE> 18%
14.	Radiography on welds prior to PWHT

Figure 11 below is the plot of the weighted scores for this section.

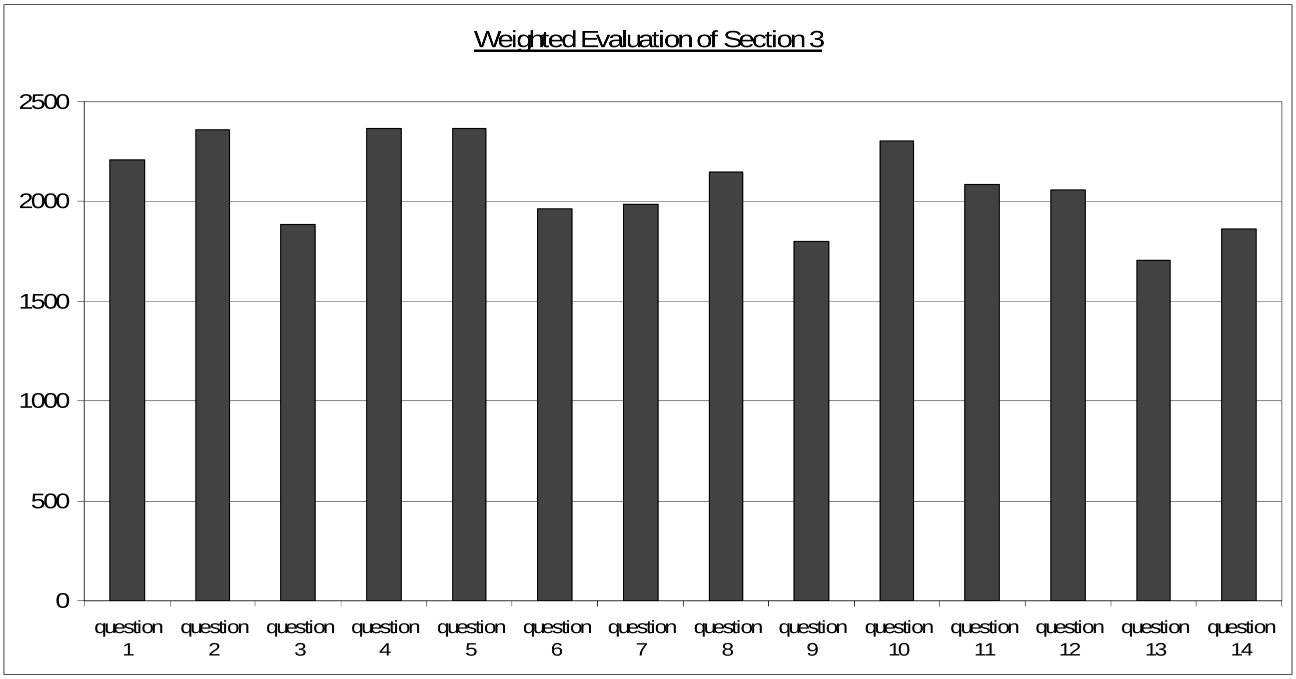


Figure 11: Weighted Evaluation of Section 3 of the Questionnaire

From the plot it is observed that the weighted scores for the majority of the questions are in the same region. The highest weighted scores were for questions 1, 2, 4, 5 and 10.

Question 1 asks whether a corrosion allowance on carbon steels affects vessel integrity. The specification dictates a 3 millimetre allowance unless otherwise stated. Question 2 asks whether stress relieving heads when formed affects vessel integrity. Questions 4 and 5 address attachments to the shell. The former asks whether material compatibility, in terms of welding, affects vessel integrity and the latter asks whether dissimilar materials forming a galvanic cell in electrolytic conditions, affects vessel integrity.

Figure 12 below illustrates the plot for the average value scores for section 3 of the questionnaire.

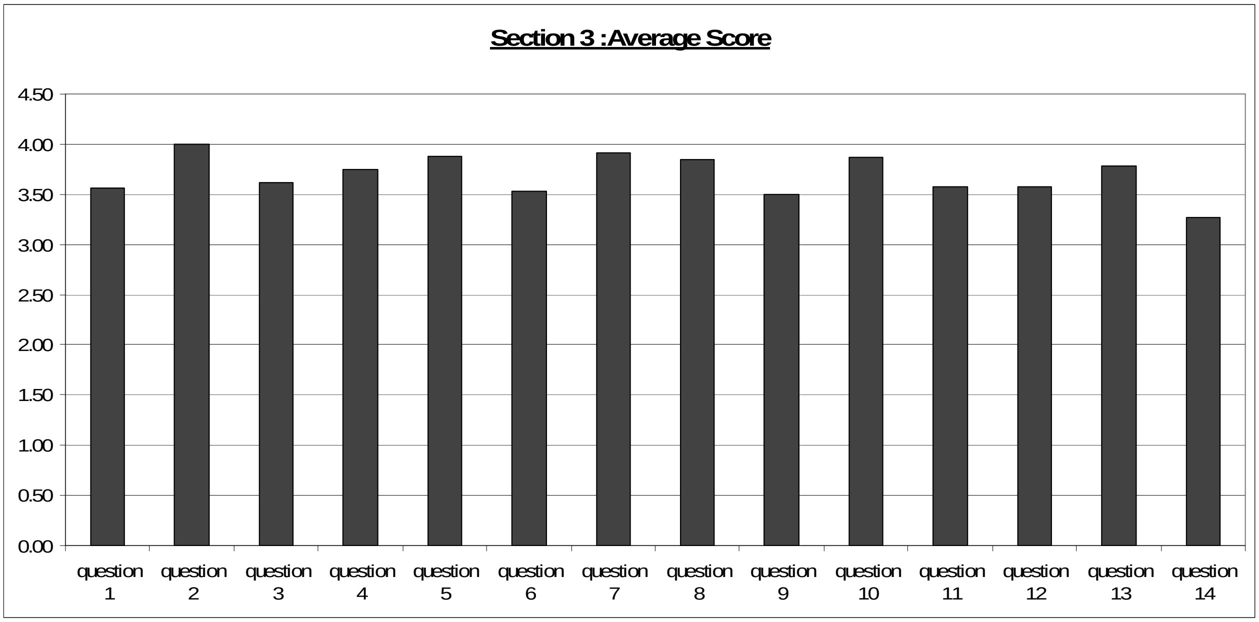


Figure 12: Average Scores for Section 3 of the Questionnaire

From the plot for the average scores it can be seen that the scores are in the range of a 3 and 4 rating, so the overall scoring is that all the requirements as listed regarding material selection and quality in this section of the questionnaire somewhat affects or has an important effect on the integrity of a vessel.

Of the high ranking questions, questions 2 and 5 are once again prominent. The respondents' opinion with regards to the requirements for material selection and quality in the specification for all the questions is average to high. Based on average scores, the SASOL respondents rated this parameter as having an important to having an extreme effect on vessel integrity.

5.1.4 Section 4 – Welding Specifications

This section deals with specification requirement that affect the manufacture of vessels, with specific reference to the welding of vessels. The welded joint is the weak point in the pressure vessel construction, and so this becomes an important component of pressure vessel design. The specifications that were ranked for this section can be viewed in table 6 below.

Table 7: Table of Welding Specifications

	SPECIFICATION REQUIREMENT
1.	Weld toe-to-toe clearance to be greater than 50mm or 2T whichever is greater
2.	Load bearing attachment welds to the shell to be full penetration welds
3.	Weld finish to be fatigue finish for welds in cyclic service
4.	Simulated PWHT required (other than code) on plate, piping, custom made forgings and standard fittings (ITP02-1)
5.	Vessel material in Sasol Low Temperature Service (NOT Code) to be PWHT
6.	PWHT required for vessels in Amine service
7.	When attachment welds cross shell weld seams the weld seam is to be ground flush 50mm either side of the attachment with 100% RT and MT/PT done prior welding the attachment
8.	Austenitic stainless steels in corrosive service shall be of the low carbon or stabilised grades

Figure 13 below is the plot for the weighted evaluation of these questions.

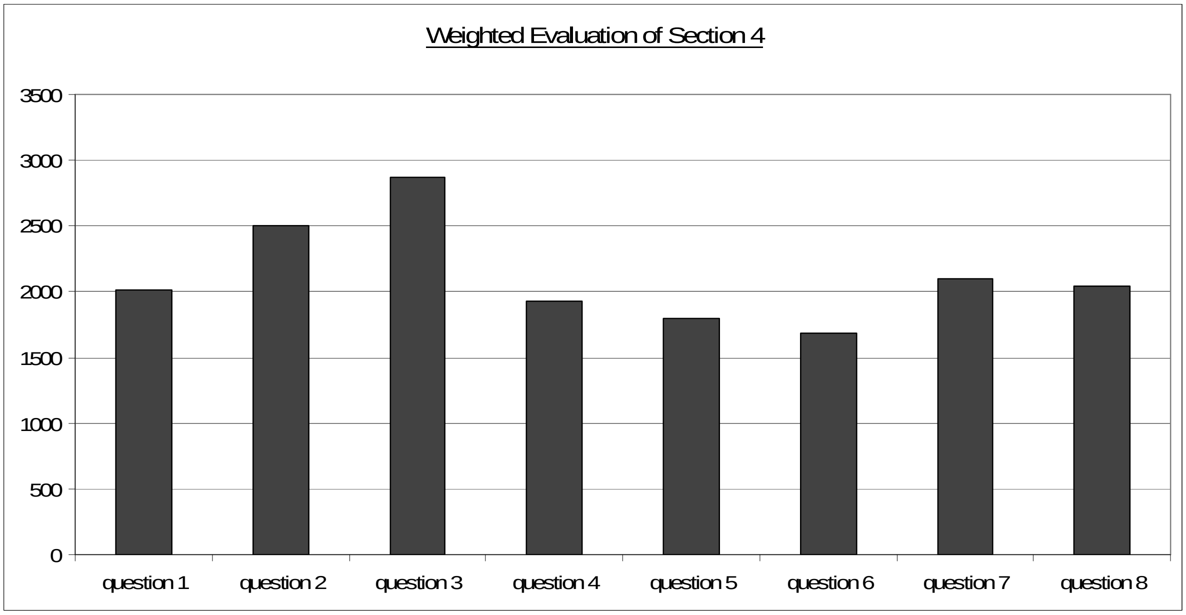


Figure 13: Weighted Evaluation of Section 4 of the Questionnaire

From the graph of the weighted evaluation for the questions, it is clear that questions 2 and 3 are highly rated questions. Question 2 asks whether load bearing attachment welds to the shell should be full penetration welds as opposed to fillet welds. Question 3, weighted the highest of the all the questions asks whether fatigue finishing of welds in cyclically loaded conditions affects vessel integrity.

The question with the lowest weighting was question 6, which dealt with the Post Weld Heat Treatment of carbon steels when used in amine service.

Once again, the results from the average scores need to be looked at. Figure 14 is the plot of the average scores for section 4 of the questionnaire.

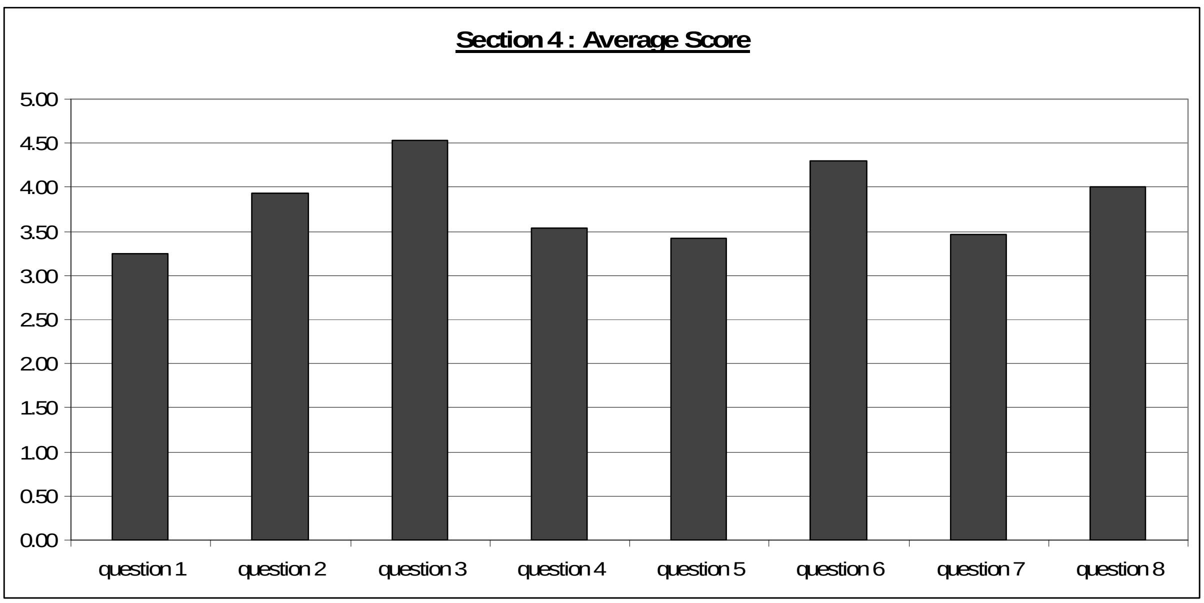


Figure 14: Average Scores for Section 4 of the Questionnaire

It can be observed that the highest average scores are for questions 2 and question 6. The high average score for question 2 corresponds to that of the high weighted evaluation. On the contrary, the high average score for question 6 does not correspond to the weighted evaluation for this question. From an evaluation of the raw data, it can be seen that only ten of the respondents felt it within the scope to evaluate this requirement. This explains the low weighting for the question. The ratings that were however captured for this question were either a 4 or 5 from the ten respondents. This evaluation indicates then that the respondents rated this requirement as having a considerable effect on vessel integrity.

What also can be observed in Figure 14 is that once again, the respondents' scores for requirements that deal with welding and its effect on vessel integrity are on average highly rated.

The respondents' opinion with regards to the requirements for welding requirements in the specification for all the questions is average to high. Based on average scores, the SASOL respondents rated this section as having an important to having an extreme effect on vessel integrity.

5.1.5 Comparison of Philips and Warwick Data to Questionnaire Results

The top ranking specifications from the questionnaire can be seen in table 8 below.

Table 8: Table of Top Ranking Specifications from Questionnaire

Respondent Ranking of Grouped Specifications	*Weighted Average as a % of total*
Design and Constructability:	
- Integral reinforcement on high pressure and high temperature pressure vessels	7.67
- Skirt to shell weld on tall vessels to be fatigue resistant	7.32
- Cyclic loaded vessels to have lip type forgings	7.27
- Full penetration welding of nozzles 3" and larger for nozzle to shell weld	7.21
Material Selection and Quality:	
-Stress relieving of formed heads	7.75
-0.25% max carbon content for carbon steels	7.57
-No dissimilar metals welds in process service	7.5
-Re-certification of hot formed parts	7.49
Welding:	
-Fatigue finish of welds in cyclic service	14.89
-PWHT for welds in amine service	14.12
-Corrosive service austenitic stainless steel to be of low carbon or stabilized grade	13.14
- Load bearing attachment weld to be full penetration welded to vessel	12.93

It is observed that with respect to design and constructability, the requirements that the respondents ranked highest addresses the design of weldments. The top ranking requirement is the use of integral reinforcement as opposed to compensation pad reinforcement for nozzle openings. This reduces the amount of welding on the vessel. The requirement that addresses the weld design of the head to skirt attachment welds for process vessels classified as being slender, i.e. a length over diameter ratio of greater than 10, was ranked second highest. Here, attention to the weld is given to ensure that fatigue cracking does not occur. The third highest ranking requirement addresses the connection detail of nozzles where cyclic loading occurs. In this case the nozzle to shell attachment weld is changed from a corner weld to a full penetration butt weld, where the root can be inspected, and takes the weld away from the area that would see the highest stresses during nozzle loading and so reduces the risk of crack generation in the weldment of the corner weld. The fourth highest ranking requirement addresses the nozzle to shell attachment weld for all services. The requirement states that all nozzles 3 inch and larger should be attached to the vessel using a full penetration butt weld. The change from a fillet weld to a butt weld is to remove the uncertainty of the stress raiser that might occur at the root of the fillet weld that could cause a crack to propagate.

In the section on material selection and quality, the requirement ranked the highest addresses the stress relieving of formed heads. Residual stresses induced during the forming process need to be relived and stress relieving the head ensures that residual stresses are relieved and do not result in crack formation in the heads. The second highest requirement in this section addresses the maximum carbon content for carbon steels. The carbon content of steels affects the weldability of the steel, making the weldment harder and more brittle. The maximum limit on carbon content is therefore used to ensure that brittle zones, prone to cracking do not form. The requirement ranked third highest addresses the welding of dissimilar metals. This is prohibited for welds in contact with the process since a galvanic corrosion could result. The re-certification of hot formed parts was the fourth highest ranked requirement and addresses the issue of ensuring that hot formed parts are restored to original material properties using certification to record the process.

In the section on welding, the highest ranked requirement addresses the finish of welds in cyclic service. The welds are to be fatigue dressed, i.e. the weld is to ground to a smooth even transition and no stress raisers are allowed. This requirement ensures that no area of the weld is prone to cracking. The second highest requirement addresses the Post Weld Heat Treatment (PWHT) of welds in amine service. Here, again the weld is relieved of residual stresses to ensure that the weld is not prone to cracking. The third requirement addresses the use of stainless steels in corrosive services. The requirement ensures that low carbon content or stabilized stainless steels are used for these applications. The focus is on reducing the possibility of carbon rich zones forming at welding sites, and therefore it reduces the susceptibility to preferential corrosion at these areas. The fourth highest requirement ensures that load bearing attachment welds to the shell be full penetration. This ensures that fillet welds are not used as they can crack into the shell material if a load is applied.

5.2 Historical Process Column Data Analysis

The first task was to locate the process columns on the processing units within the Refinery area of SASOL Synfuels. There are fourteen types of processing plants within the complex of which eight of the units exist in duplicate.

For the purposes of this research, *defect/defective* is used when referring to a process column that has had a material investigation done to confirm concerns regarding material state/condition.

Figure 15 illustrates the number of process columns per processing unit at the refinery.

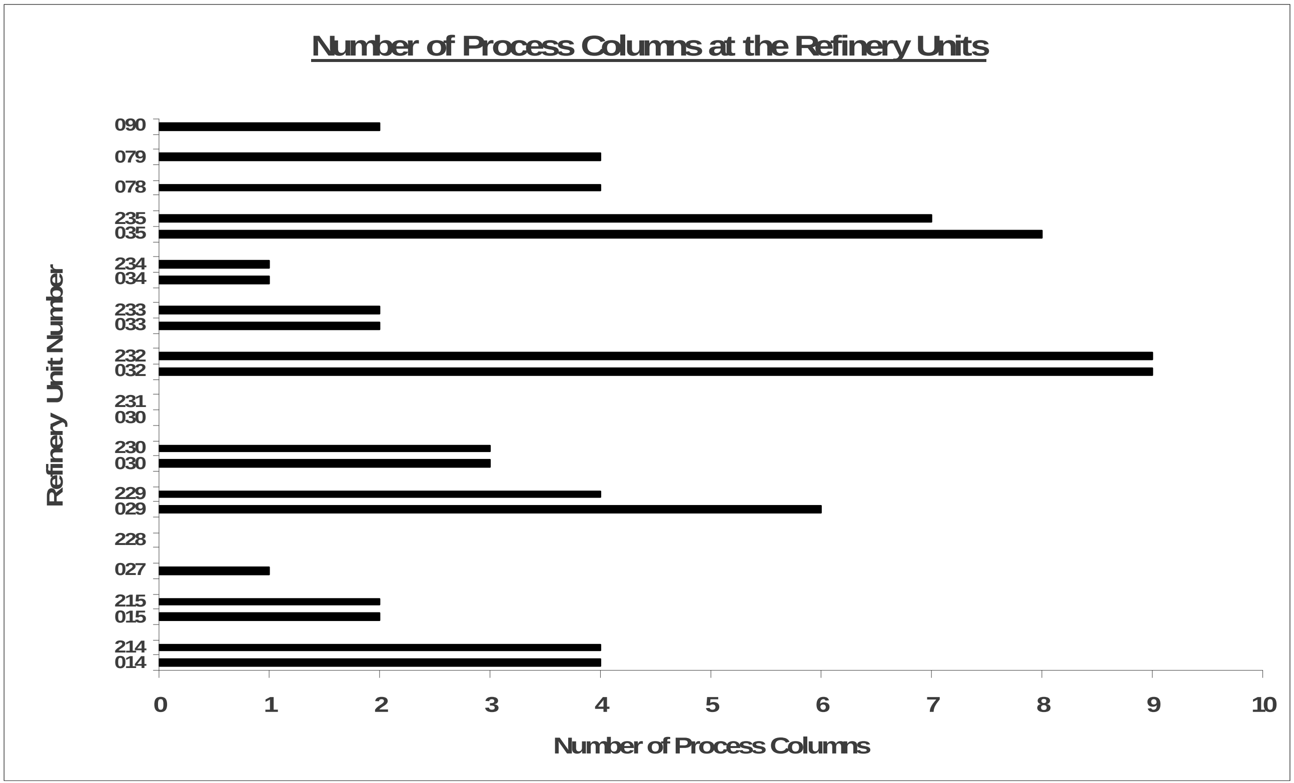


Figure 15: The number of columns within the Refinery business unit

As depicted in the graph above, the majority of the process columns lie within units X32, X35 and X29.

There are a total of seventy eight process columns within the refinery complex processing units, of which forty three of them are located within units X32, X35 and X29.
This is a fairly high concentration of process columns, when compared to the rest of the SASOL complex.

From the columns that are within the refinery, a total of 111 metallurgical reports were located in the archives at metallurgical consultants to SASOL for the columns at the refinery. These reports were analysed and key information recorded in Appendix F of this report.

Figure 16 below illustrates the number of columns on which defects were inspected over the lifetime of the units at the refinery.

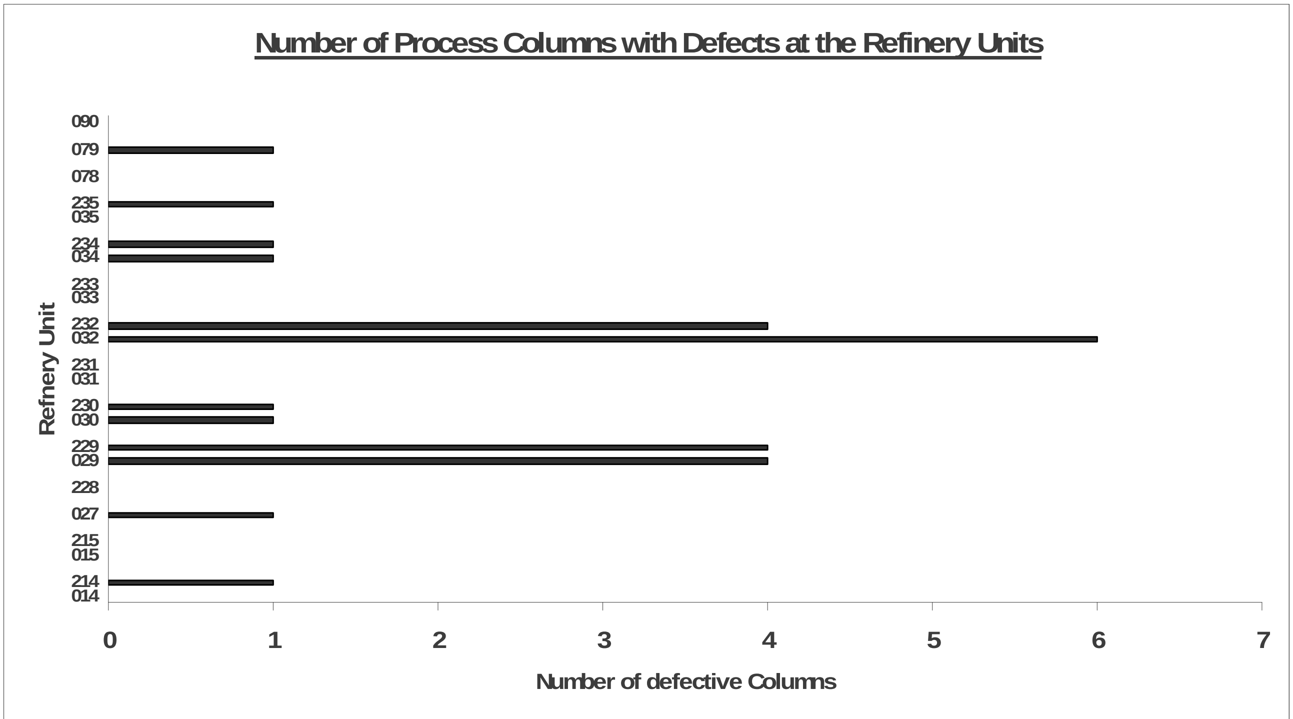


Figure 16: The number of columns with defects within the Refinery business units

From the graph, it can be seen that X32 and X29 are the only units that problems with more than one of the process columns on the business units. The balance of the units experienced problems with only one specific column, or has not experienced problems at all. Of all the data gathered, unit X34 is the only unit that experienced the same problem on both the eastern and western units.

5.2.1 Column Specific Defects

The following section discusses in the detail the observations that were made during the analysis of specific column data for the refinery. The columns are discussed in numerical order according to refinery unit number and only major issues are discussed, a full list of defects can be reviewed in Appendix F.

214VL-102

The problem that occurred on this column was that the fillet weld on an internal attachment inside the column had cracked. The attachment was removed, re-fitted and then re-welded.

27VL-101

In 1992 the function of the column was changed to a steam stripper, the process contained acids and an investigation was done determine what the impact on the material would be. The finding was that the carbon steel would be suitable for the service without any additional requirements.

X29VL-101 (two columns)

Both the process columns (carbon steel) on the eastern and western plant have, from the commissioning of the columns, displayed degradation of welds, nozzles and shell material due to corrosion induced by acids present in the process. The column internals have been replaced as well as various nozzles. The bottom section of the column was replaced in stainless steel. Later, the entire column is replaced in carbon steel.

29VL-103

The material of the top section of this carbon steel column is recommended for replacing in stainless steel based on the results from the 101 column.

X29VL-104 (two process columns)

The process column displays a history of excessive material damage in various sections. This is due to corrosion based on acid present in the process stream. The bottom section of the column was replaced in stainless steel. At one stage the trays in the column had collapsed due to galvanic corrosion on bolt material. The grade of stainless steel used varied between three grades in the columns and only the correct grade did not corrode.

X29VL-105 (two process columns)

This column was reported to have organic acid corrosion of the based material (carbon steel), as is the case with the 101 and 104 columns. It however also displayed weld areas that were being preferentially being corroded. The weld filler material that was used was of a different galvanic value to the base material, and hence the acids preferentially corroded the welds where the galvanic cell existed.

229VL-106

The only reported history on this column was the record of a material change on the nozzles.

30VL-101

Indications were observed inside the manhole, at the nozzle to shell weld. It appeared to be a manufacturing flaw and was ground out and weld built up.

X32VL-105 (two process columns)

The column has a history of severe laking and pitting corrosion on the shell base material and in the areas of the nozzles (carbon steel). The material for the shell was incorrectly selected for the phosphoric acid in the process stream. The column is continually cleaned and repaired at shutdown; in addition a thermal metal coating was applied to reduce the effect of corrosion. The material selection of this coating has also not been correctly selected and has had repairs as well.

X32VL-106 and 206 (four process columns)

These process columns, as is the case with the 105 columns, have an incorrect base material selection (carbon steel). The phosphoric acid in the process stream continually corrodes the shell base material and the nozzles, and at shutdown, weld repairs are necessary.

X34VL-101 (two process columns)

The internal Glitsch packing has a history of being corroded and replaced. The organic acids present in the streams. The grade of stainless steel used for the columns was replaced by a better grade of stainless steel.

79VL-103

Significant corrosion was noted inside this column, with preferential corrosion on the inlet nozzle to shell weld. Once again this is as a result of organic acids in the column's process stream.

5.2.2 Data Analysis

This section investigates the results of the historical data that was captured for the process columns. Figure 17 is a combination of the data as illustrated in Figure 15 and Figure 16 above.

From the graph it can be seen that majority of the columns on units X29 and X32 have had defects over its lifetime. What is also noticed is that eleven of the twenty three units have a column/s that has a defect i.e. forty eight percent of the units.

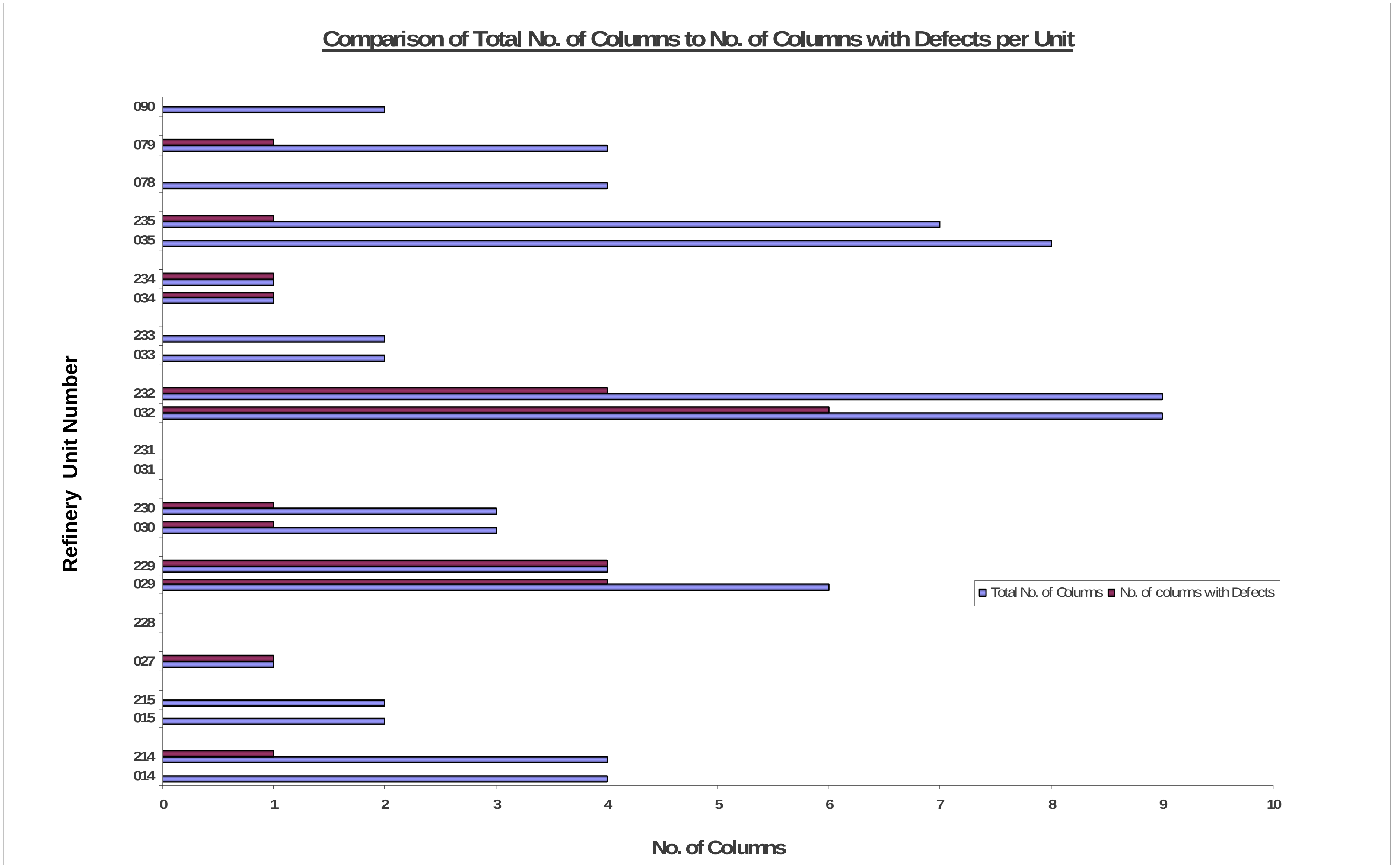


Figure 17: Comparison of Total No. of Columns to No. of Columns with defects per Refinery Unit

Table 9 below is a tabulation of the results with the associated percentages for the results in figures 15, 16 and 17.

Table 9: Tabulation of Summary of Historical Data Results

Unit	Columns		
	Total	**Defective**	**% Defective**
014	4	0	0
214	4	1	25
015	2	0	0
215	2	0	0
027	1	1	100
228	0	0	0
029	6	4	66.67
229	4	4	100
030	3	1	33.33
230	3	1	33.33
031	0	0	
231	0	0	
032	9	6	66.67
232	9	4	44.44
033	2	0	0
233	2	0	0
034	1	1	100
234	1	1	100
035	8	0	0
235	7	1	14.29
078	4	0	0
079	4	1	25
090	2	0	0
	78	**26**	**33.33**

What is clear from the table is that of the seventy eight columns within the refinery, i.e. twenty six of the columns experienced defects on site. This is around thirty three percent of the columns installed on the east and west processing plants.

Also, units X29 and X32 both have the highest number of columns on the unit, but also display a high number of columns with defects. These units alone account for twenty three percent of the columns with defects within the refinery area. This leaves a balance of about ten percent from the balance of the units.

What is also noticeable is that there is a good spread of columns with defects across the entire refinery at forty eight percent of the units having defective columns.

What was observed from the physical reports is that most of the corrosion cases are as a result of an acid present in a process stream that has not been considered during the material selection for the column during the design phase. It is also noted that in two cases, the process was intentionally changed and the impact of the change investigated.

What is also clear is that most of the columns would corrode in the bottoms section of the column, around nozzle welds and at weld seams. The material used for internal column processes has also been compromised when the material selection has not been considered during design.

5.3 Process Column Cost Data Analysis

The costs in this section of the report have been factored to protect the interests of SASOL. The aim is a qualitative comparison, rather than a quantitative cost analysis. Because of this, a standard interest rate of ten percent was used as a basis for comparison.

The costs were obtained from SASOL historical data storage. The costs therefore only include amounts recorded. Based on the historical defects/repair data it was seen that numerous costs were not accounted for. Of all the costs investigated, the author chose four process columns that have the most complete costing data.

Because of the quantitative nature of the data, the costs were based on three data sets.

i) *Costs Incurred Discounted to Initial Capital Costs*
   This data set was based on discounting the actual costs over the life cycle of the vessel to the date of the initial capital cost of the vessel. These costs were then plotted as life cycle costs added to the initial capital cost. The plot graphically displays the fluctuation in costs over the life cycle, the aim being to identify major costs.

ii) *Cumulative Costs Based on Actual Costs*
   This data set was based on a cumulative cost of the recorded costs of the vessel. It plots actual costs (not discounted) in a trend for the costs over the life cycle of the vessel. The reason for using this plot was to compare the trend with that of the plot for cumulative costs based on discounted values.

iii) *Cumulative Costs Based on Discounted Values*
   This data set was based on the cumulative cost values, discounted to the same timeline. These costs were then plotted for a trend analysis.

Four columns were chosen for investigation based on the completeness of the costing data. The columns were 29VL-104, 29VL101, 229VL-101 and 30VL-101.

The costing data can be viewed in Appendix G.

5.3.1 29VL-104

Figure 18 is the graphic plot of the values of costs, discounted back to the date of manufacture. Over the life cycle of this column, a significant cost is observed at cost nine, twenty-two years after the manufacture of the column. This cost was recorded and accounted for as a material and weld repair cost for the column.

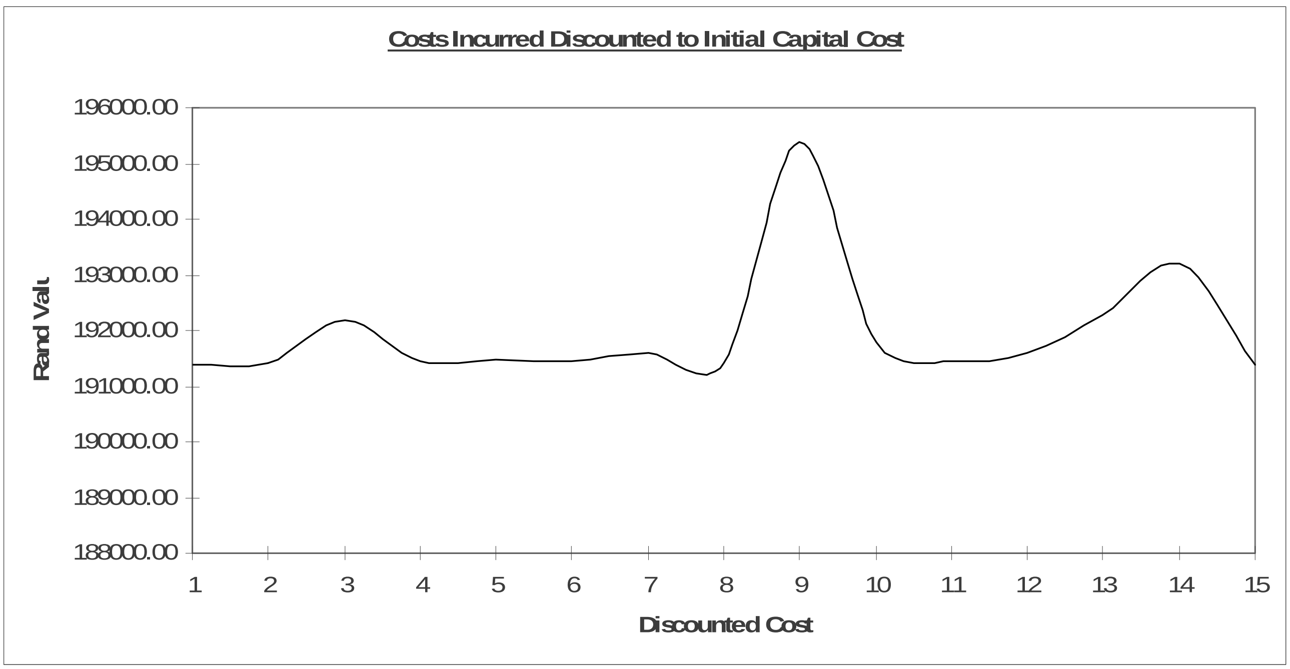


Figure 18: 29VL-104 Costs Incurred Discounted to Initial Capital Cost

It can be observed that thirteen of the fifteen costs recorded are insignificant when compared to initial capital cost of the process column. At a discount rate of 10%, the percentage of initial costs that cost nine represents is 2% of the initial capital cost. When the discount rate is adjusted to 5%, the percentage of initial capital cost that cost nine accounts for is 5.8%.

Figure 19 plots the cumulative costs of the process columns based on the actual costs incurred over the lifetime of the column. A distinct increase at costs nine and fourteen is observed.

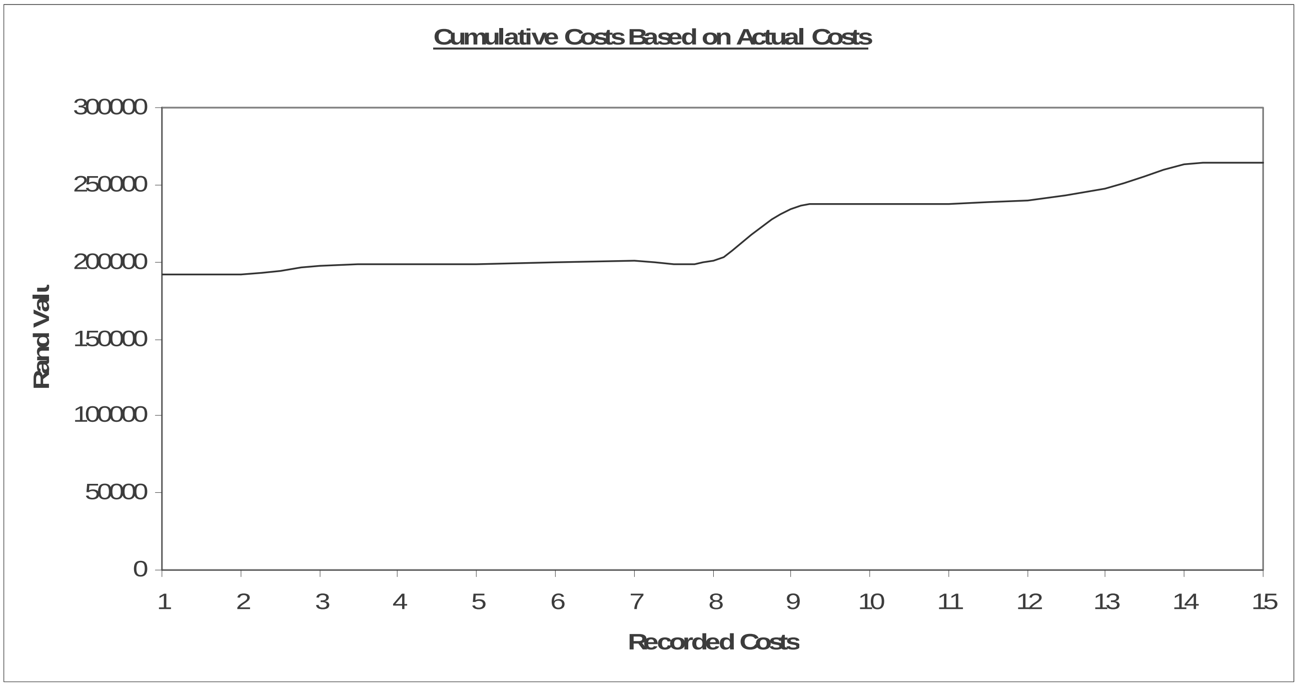


Figure 19: 29VL-104 Cumulative Costs Based on Actual Cost

Figure 20 is the same cumulative cost plot as figure 19, except that the costs are discounted by 10% to the initial manufacture of the column. What is immediately obvious is that the trend for the plot in figure 20 is identical to that of figure 19, except for the magnitude. So even though the discount rate might not represent what the actual discount rate was, the trend of costs observed is still valid.

The author will therefore use only the plot of cumulative costs based on discounted values in the analysis in the research for the remaining process columns.

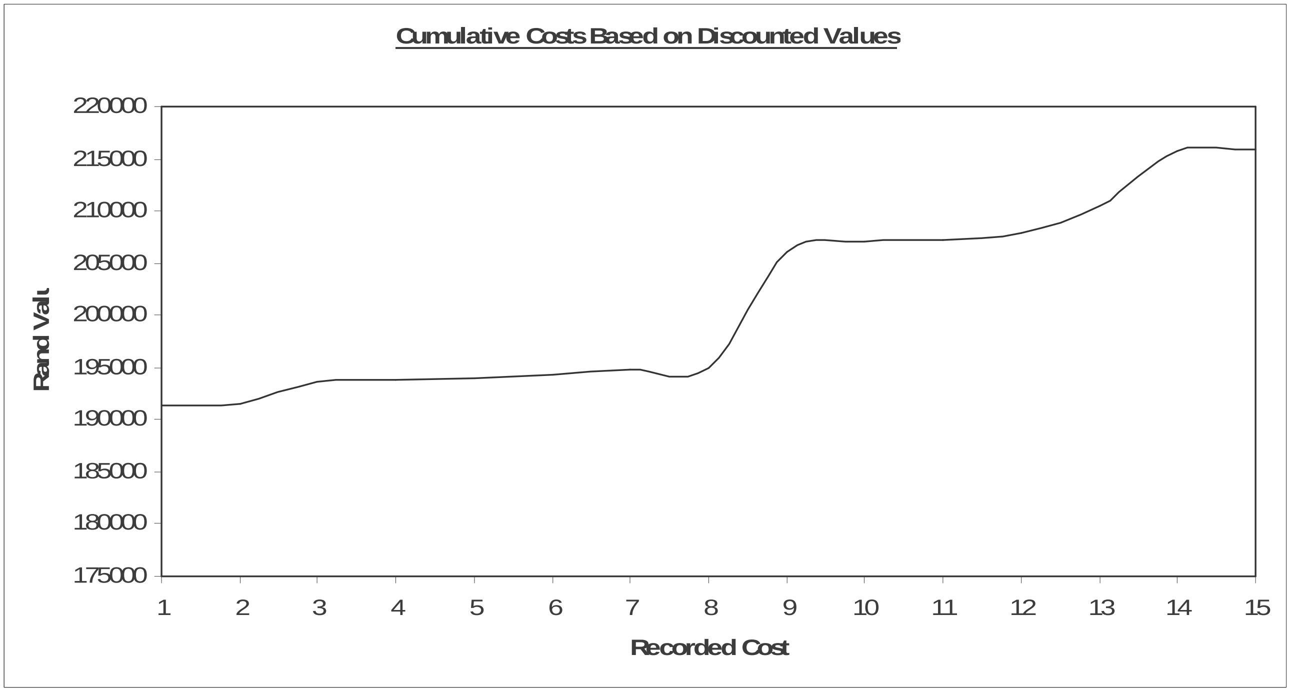


Figure 20: 29VL-104 Cumulative Costs Based on Discounted Values

Based on the values of figure 20, the total recorded costs over the life cycle of the process column, accounts for 4.5% of the total initial cost of the column.

Some of the costs not accounted for in the historical costing data, but that were referenced in the metallurgical data (see Appendix F), include significant costs for the replacement of the bottom half of the column in a new material based on acid corrosion on the initial carbon steel construction. The same was experienced with the trays in the column, and they were replaced six and a half months after the column was commissioned. In 2005 corrosion of the bolts led to a collapse of the trays and they were again replaced.

These very significant costs, as well as the downtime cost of the unit, based on the collapse of the trays was not recorded or accounted for in the costs for this unit. All costs recorded in Appendix F for this column are directly related to corrosion problems experienced on the vessel.

5.3.2 29VL-101

Figure 21 is the graphic plot of the values of costs, discounted back to the date of manufacture. Over the life cycle of this column, a significant cost is observed at cost eight, twenty-two years after the manufacture of the column. This cost was recorded and accounted for as a material cost for the column.

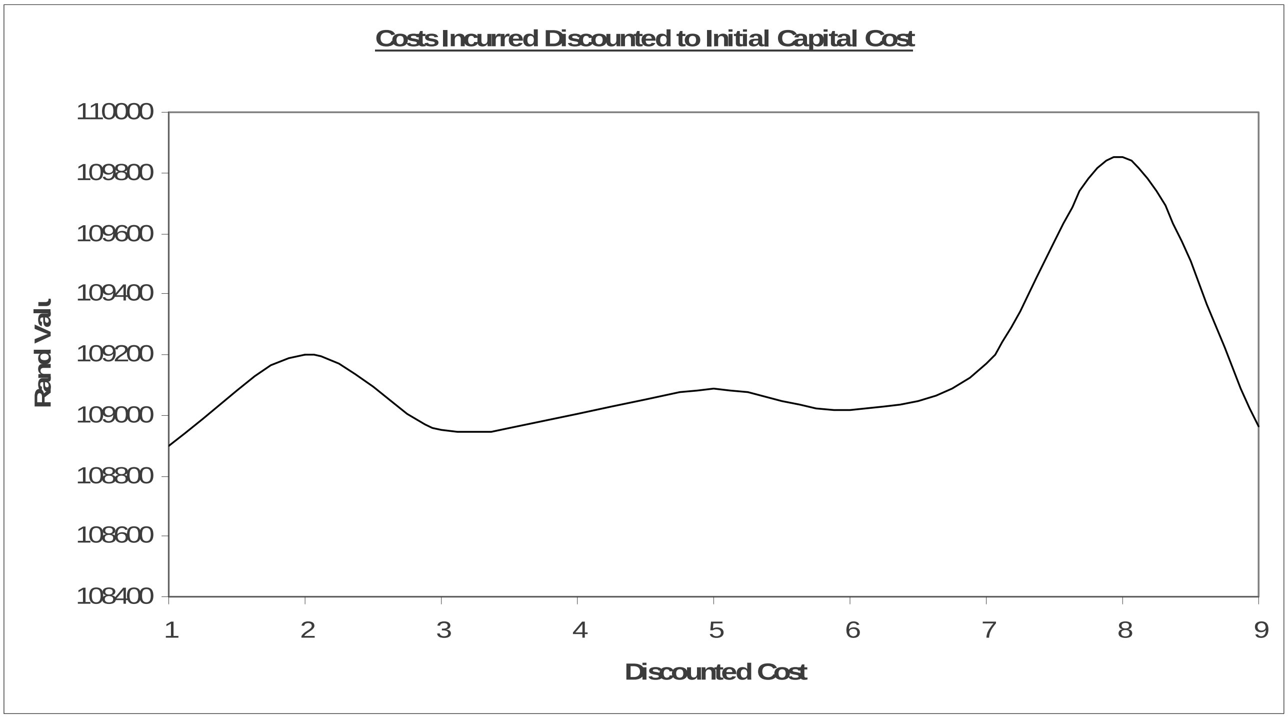


Figure 21: 29VL-101 Costs Incurred Discounted to Initial Capital Cost

From the graph, cost eight is the most significant recorded cost. This cost only however represents 0.875% of the initial capital cost. This figure is fairly small when compared with the initial cost of the vessel.

Figure 22 is the cumulative cost plot, discounted by 10%, to the initial manufacture of the column.

It is again clear that over the life cycle of the column; only nine costs are recorded for the life of the column. The total recorded costs account for only 1.88% of the initial capital cost of the column.

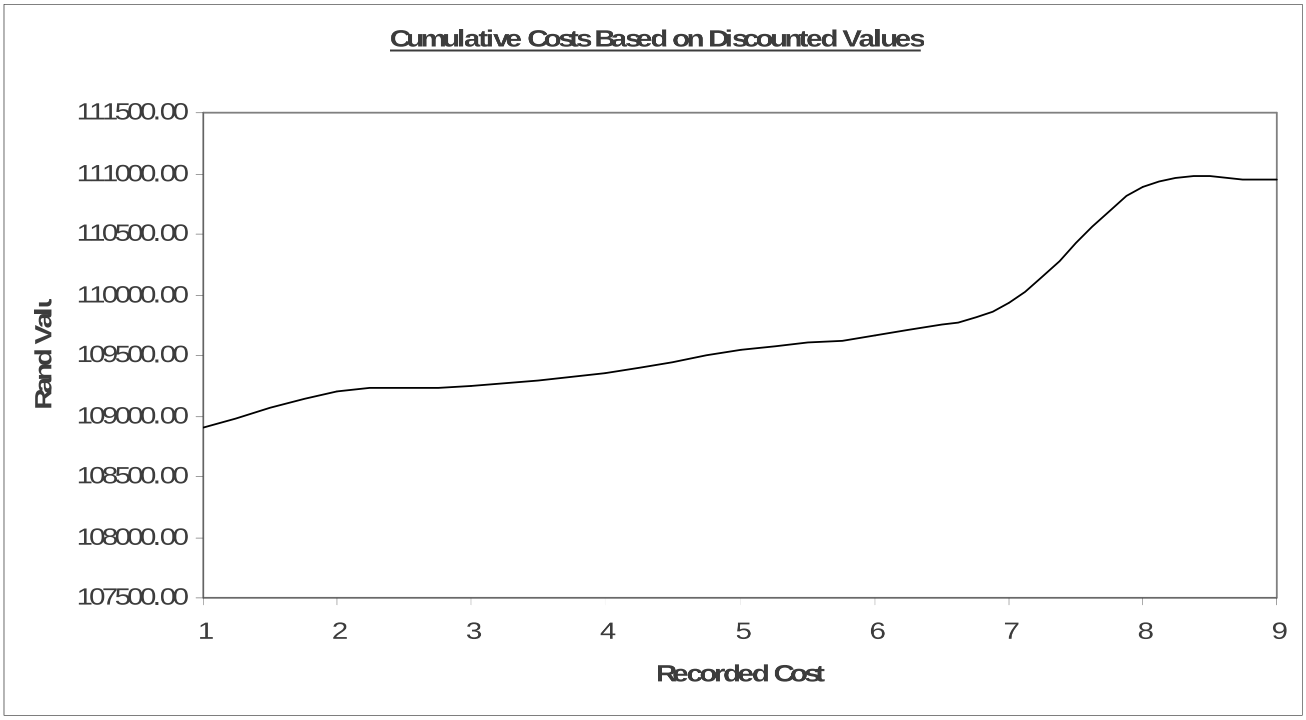


Figure 22: 29VL-101 Cumulative Costs Based on Discounted Values

When the data is compared to the data of Appendix F, It is seen that the cost for the replacement of the internals as sell as the tray rings (in 1990) is not accounted for in the recorded costs for the vessel. The other costs seen in Appendix F for this column related to a process change upstream of the unit.

Once again, the recorded costs for this column indicate that the costs over the life cycle are insignificant, but the metallurgical reports indicate significant costs attributed to corrosion that are not accounted for over the life of the column.

All the reports in Appendix F for this column also are as a result of corrosion.

5.3.3 229VL-101

229VL-101 is identical to 29VL-101; its site location is on the mirror image of the 229 unit. Figure 23 is the graphic plot of the values of costs, discounted back to the date of manufacture. Over the life cycle of this column, a significant cost is observed at cost fifteen, twenty-two years after the manufacture of the column. This cost was recorded and accounted for as a material cost for a section replacement of the column. When compared with the other costs for the column, this cost is the most significant.

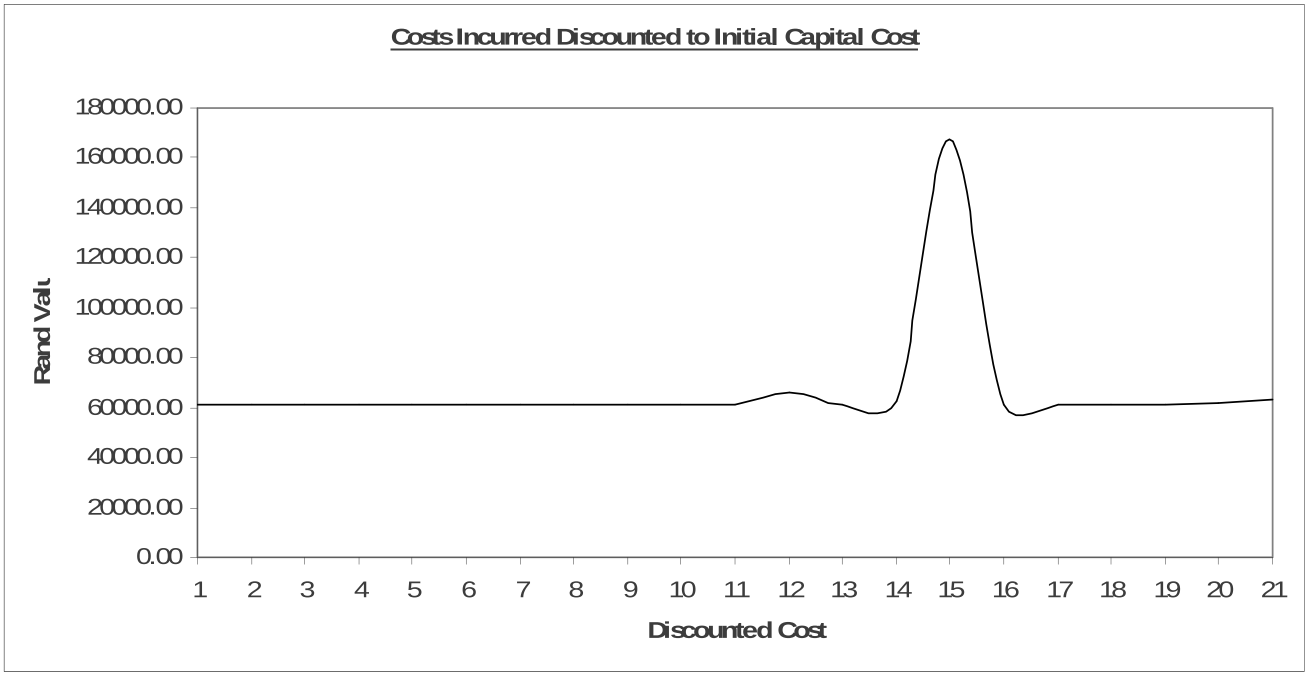


Figure 23: 229VL-101 Costs Incurred Discounted to Initial Capital Cost

When compared to the initial capital cost of the process column (and discounted at 10%) it is observed that the cost of this section replacement is 174% of the initial capital cost of the vessel.

The other costs that are accounted for and are significant are for nozzle replacements and repairs on the column due to corrosion.

Figure 24 clearly indicates the jump in costs based on the column section replacement at cost fifteen.

This column's cumulative costs over its life cycle are 195% of the initial cost (discounted at 10%).

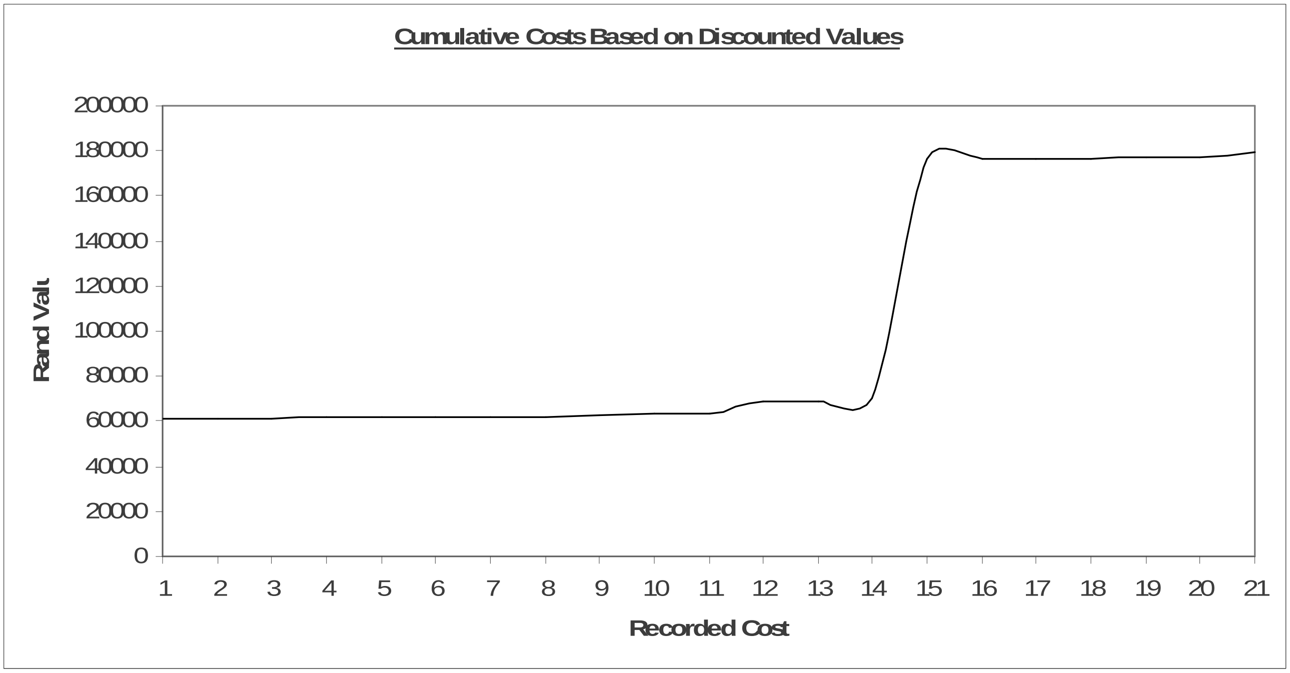


Figure 24: 229VL-101 Cumulative Costs Based on Discounted Values

When the costs are compared to the data of Appendix F for this process column, a significant cost for the total replacement of the column in stainless steel is not reflected in the recorded costs for this column. Once again all the reports recorded for this unit were as a result of corrosion.

5.3.4 30VL-101

Figure 25 is a plot of the values of costs, discounted back to the date of manufacture for 30VL-101. Over the life cycle of this column, the highest cost incurred is observed at cost eight, twenty-seven years after the manufacture of the column. This cost was recorded and accounted for as a cost for inspection on the column.

It can also be observed only eight costs were recorded over the life cycle of this process column.

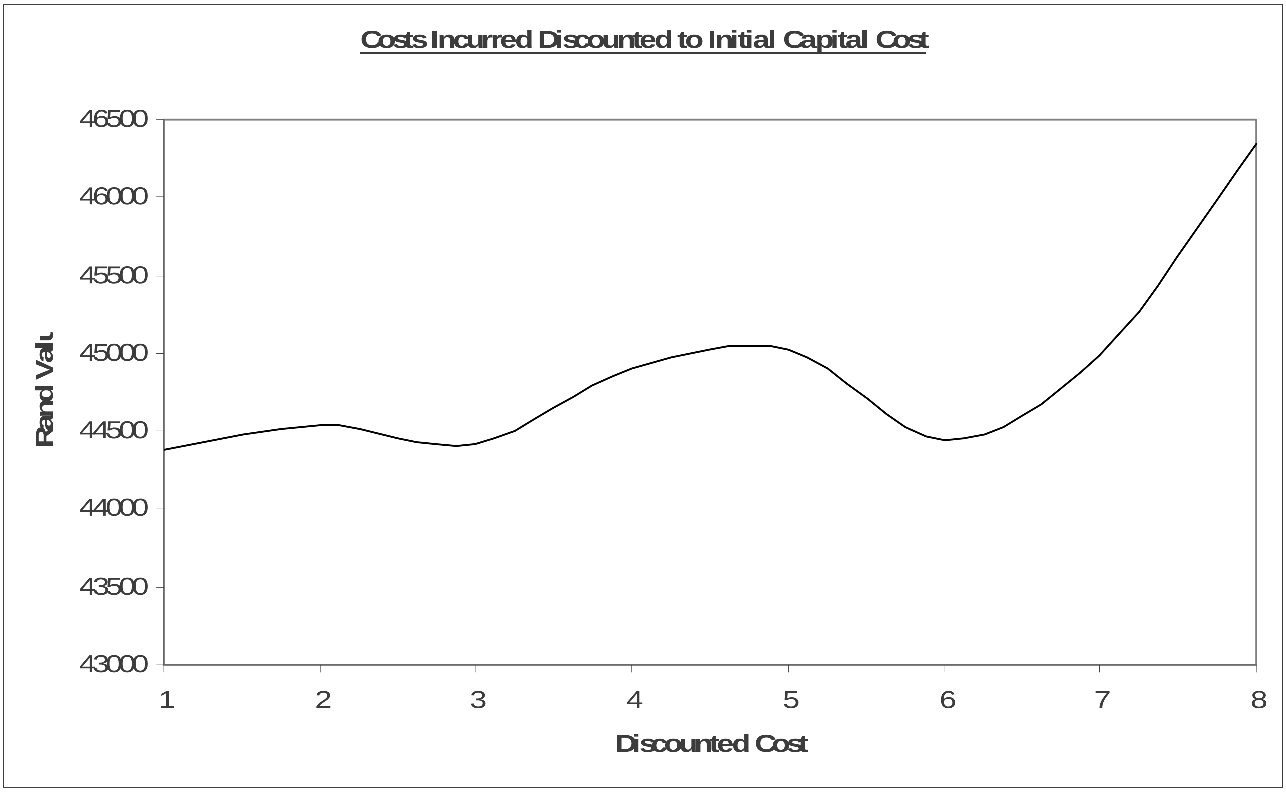


Figure 25: 30VL-101Costs Incurred Discounted to Initial Capital Cost

Cost eight represents 4.4% of the initial capital cost of the process column (discounted at 10%).

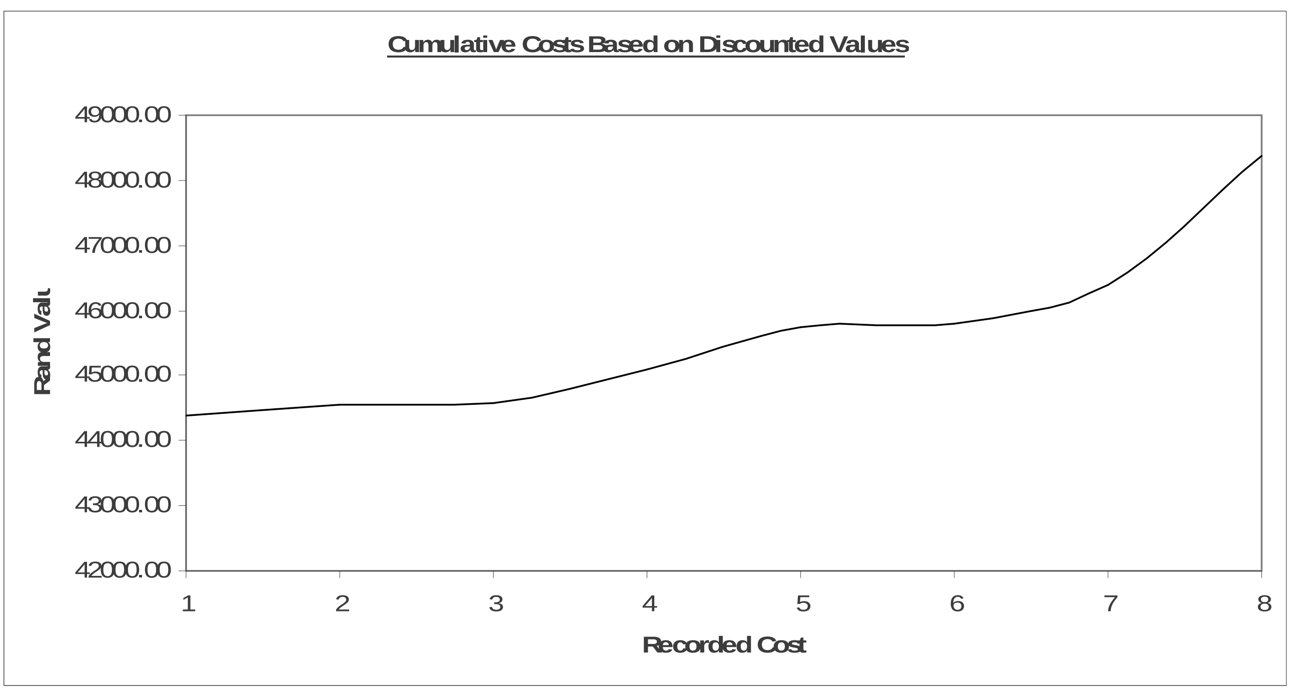


Figure 26: 30VL-101 Cumulative Costs Based on Discounted Values

The total cost cumulative cost incurred for this process column accounts for 8.98% of the initial capital cost of the vessel. The majority of the costs were recorded against material costs as a result of corrosion, with two costs recorded as inspection costs.

5.4 Evaluation of Results

The data used to substantiate the results was taken from three distinct sources viz. a) the opinion of respondents on the impact of technical specifications on technical integrity of process vessels, b) historical defect and repair reports recorded for the inspection of the process columns in the refinery area, and c) the actual costs captured by the business unit for the process columns.

In the section on design and construction specification requirements, the opinion was that the requirements for attachments to pressure vessels as well welding details had the highest impact on the technical integrity of process vessels.

When the results from the respondents is compared with the Phillips and Warwick data it immediately is seen that ten of the twelve requirements rated by respondents as having the greatest impact on vessel integrity relates to preventing crack formation in the vessel material. When the Phillips and Warwick data is considered, we see that 89.3% of the total cases causing failures, results from cracks. On further investigation of the reason for these cracks, it is observed that fatigue constitutes the largest cause at 35.6% of the total number of cases. Three of the twelve SASOL specification requirements address fatigue specifically. The second highest cause for cracking in the Phillips and Warwick data is corrosion at 18.2%. When the results from the respondents is analysed, it is observed that four of the top twelve ranked SASOL requirements addresses cracking as a result of corrosion.

When this data was compared with the data for the historical defects/repair reports for the process columns, it was observed that in many cases, the welding was the first area to corrode in a corrosive environment. None of the process columns have a recorded case for shutdown due to weld failure, but many of the columns have continuous weld repairs recorded over the life cycle.

When the cost data is considered, it is clear that the area of weld build up is one that occurs throughout the life of the process column, but the costs associated with this activity is very small when compare to the initial capital cost of the vessel.

In the section on material selection and quality specification requirements, the opinion was that the requirements for corrosion allowance, stress relieving and attachments to the pressure envelope were rated as having the highest impact on technical integrity of the process columns.

When this data was compared with the data for the historical defects/repair reports for the process columns, it was observed that in all cases, the weld ligament was the first area to corrode in a corrosive environment. None of the process columns have a recorded case for shutdown due to weld failure, but many of the columns have continuous weld repairs recorded over the life cycle of the process column.

When the recorded costs were compared with that of the defects experienced, it was observed that most of the costs related to corrosion of the main shell or components attached to the shell. Most of the maintenance effort and repairs were therefore as a result of corrosion. These costs, when compared with the initial capital costs of the process columns still accounted for a small portion of the initial capital cost.

In the section on welding specification requirements, the opinion was that the requirements for full penetration welding used for load bearing attachments had the highest impact on technical integrity as well as the finishing of welds in fatigue service.

When this data was compared with the data for the historical defects/repair reports for the process columns, it was observed that in many cases, the weld joint was the weak point in the system. As was the case with the material and quality requirements, the cost data recorded for the columns indicate a continuous maintenance effort for the repair of welds and corrosion in the process columns. These costs were very small when compared with the initial capital cost of the process columns.

When the data for the defects and repairs, based on inspection reports, and the actual costs were compared independently of the specification requirements, there was an overwhelming indication that corrosion was a problem in various units of the refinery.
The most significant costs incurred over the life cycle of the process columns were as a result of corrosion based on acids in the process streams that were not identified during the design of the unit.

From the data investigated it is deduced that the SASOL technical specifications do have an impact on the life cycle costs of the process columns in the refinery area. The costs directly related to the specification requirements are minimal when compared to the initial capital costs of the process columns.

It is further deduced that a lack technical specification in the area of material selection based on process information has resulted in excessive life cycle costs for process columns in the refinery area. The life cycle cost saving for good upfront technical specification in terms of material selection would have reduced the future costs incurred by the unit in material and even process column replacements.

6 CONCLUSIONS

Based on the findings of the data analysis section of this report, the following conclusions are drawn.

6.1 SASOL Specifications and Life Cycle Costing

SASOL specifications regarding pressure vessels have not been written taking into consideration total costs of ownership, hence life cycle costs are not captured in an effective way.

6.2 SASOL User Opinion and Actual Process Column Defects

A significant number of process vessels experienced corrosion induced failures on weld ligaments, thus corroborating the user opinion that weld design is a significant factor that impacts the technical integrity of pressure vessels.

6.3 Corrosion is the Root Cause for most Defects

Forty eight percent of the process units in the refinery area have experienced defects on process columns due to corrosion. In terms of the number of process columns, this is thirty three percent of seventy eight columns i.e. twenty six columns that have defects due to corrosion.

6.4 An Empirical Correlation between Life Cycle Costs and Technical Specification could not be Determined

The databases for costs per equipment number were not populated in a manner that allowed a full cost analysis for the process columns. The historical costing data observed was sparse and not consistent and so an empirical correlation could not be determined. What was observed for two of the columns where costs were more accurately recorded was that the life cycle costs for replacements were higher than the initial capital cost of the vessels.

6.5 Technical Specifications and the Highest Cost Areas

SASOL have not generated any specifications for the material selection of vessels based on the process description. There is no guidance on the approach to analysing the process for metallurgical impacts on materials. In most of the cases observed in the research, the presence of acids was not initially anticipated in the process for the plant. These were then identified once the equipment experienced problems due to corrosion.

7 RECOMMENDATIONS

From the conclusions of this thesis the following recommendations are made.

7.1 LCC Considerations in SASOL Specifications

Life Cycle Costing requirements need to be clarified by the originator of a specification. A decision to consider the effects of LCC also needs to be made when writing specifications.

7.2 A SASOL Specification for Material Selection Needs to be Generated

A SASOL specification guiding engineers to select the appropriate material for SASOL process streams needs to be generated. This specification should have an interface between the mechanical and process engineering departments. Aspects like chemical analysis for corrosion trace elements could be considered.

For new facilities, the process simulation needs to take in account areas where corrosion elements would accumulate. A good process definition, including corrosion elements, should be defined in the early stages of concept and basic engineering.

7.3 Data Capture for Costs Associated with Equipment needs to be Centralised

All costs associated with a piece of equipment should be recorded against the equipment tag number. Whether work is done as part of a project or as part of routine maintenance, the costs need to be reflected against the tag number.

7.4 Limitation and Further Research

The main limitation to achieve the objectives of the research was the completeness of the historical cost data for the process columns. The SASOL records for defects and repairs when compared with cost records revealed major omissions in costs of the vessel over the life cycle of the vessel.

An area for further research would therefore be to obtain a database of cost data for a different SASOL unit where the data is more complete for vessel's life cycle and to use this data together with the defects and repairs for that unit to determine empirically whether a correlation exists between technical specifications and life cycle costs.

8 REFERENCES AND BIBLIOGRAPHY

1. **Alder, J F.,** 1987. *The Effects of Fabrication Related Stresses.* The Welding Institute.

2. **Azbel, David. S and Cheremisinoff, Nicholas P.**, 1982 (Second Printing). *Chemical and Process Equipment Design.* Ann Arbor Science Publishers.

3. **Borcherds, M M., English, P J., Fielding, M L., Honikman, K S., Jacobs, Kurgan, A Z., Steyn, M E., and Van der Merwe, M N.,** 2000 (Eight Impression). *A Guide to effective spoken & written communication.* Juta & Co. Ltd.

4. **Brownell, Lloyd E and Young, Edwin H.,** 1959. *Process Equipment Design.* John Wiley & Sons, Inc.

5. **Burke, R;** 2001 (Third Edition), *Project Management Planning and Control Techniques*; Promatec Int.

6. **CCPS;** 1998; *Design Solutions for Process Equipment Failures*; Centre for chemical process safety; AICHE

7. **Chuse, Robert and Carson, Bruce E SR.,** 1993 (Seventh Edition). *The Asme Code Simplified Pressure Vessels.* Library of Congress Cataloguing-in-Publication Data.

8. **Couper, James R., Penney, Roy W., Fair, James R and Walas, M Stanley.,** 2005 (Second Edition). *Chemical Process Equipment.* Gulf Professional Publishing.

9. **Dell'Isola, Alphonse J. PE, CVS and Kirk, Stephen j. FAIA, CVS.,** 2003. *Life Cycle Costing for Facilities.* Construction Publishers & Consultants.

10. **Dhillon, B.S.**, 1989. *Life Cycle Costing.* Gordon and Breach Science Publishers

11. **Gupta, J P.,** 1986. *Fundamentals of Heat Exchanger and Pressure Vessel Technology.* Hemisphere Publishing Corporation.

12. **Hales, Crispin.,** 1993. *Managing Engineering Design*. Longman Group UK Ltd.

13. **Harvey, John F.,** 1980. *Pressure Component Construction Design Materials Application.* Litton Educational Publishing, Inc.

14. **Kletz**, T., 1998 (Forth Edition). *What Went Wrong,* Gulf Publishing Company.

15. **Lieberman, Norman P and Lieberman, Elizabeth T.,** 2003 (Second Edition). *Working Guide to Process Equipment.* McGraw-Hill Companies, Inc.

16. **Mannan, Sam.,** 2005. *Lee's Loss Prevention in the Process Industries,* chapter 12.30*,* 3rd Edition, Elsevier, Amsterdam

17. **Matthews, Clifford.,** 2001. *Engineers' Guide to Pressure Equipment.* Professional Engineering Publishing Limited.

18. **Martin, J.N**.; 1997. *Systems Engineering Guidebook*. First Edition. CRC Press. Washington DC

19. **McKetta, John J.,** 1993. *Encyclophedia of Chemical Processing and Design Volume 42 (Pre-Pro).* Marchel Dekker, Inc.

20. **McKetta, John J.,** 1997. *Encyclophedia of Chemical Processing and Design Volume 58 (The-Tra).* Marchel Dekker, Inc.

21. **Page, Carole and Meyer, Denny.,** 2000. *Applied Research Design for Business and Management.* McGraw-Hill Book Company Australia Pty Ltd.

22. **Peters, Max S and Timmerhaus, Klaus D.**, 1991 (Fifth Edition). *Plant Design and Economics for Chemical Engineers.* McGraw-Hill, Inc.

23. **Rees, D G.,** 1998 (Third Edition). *Essential Statistics.* Chapman & Hall.

24. **Sandler, Henry J and Luckiewicz, Edward T.**, 1987. *Practical Process Engineering.* Mgraw Hill Book Company.

25. **Seider, Warren D., Seader, J D and Lewin, Daniel R.,** 2004 (Second Edition). *Product & Process Design Principles Synthesis, Analysis and Evaluation.* John Wiley & Sons, Inc.

26. **Sullivan, William G., Wicks Elin M., Luxhoj, James T.,** 2003 (Twelfth Edition). *Engineering Economy*. Pearson Education International.

27. **Theilsch, Helmut,** *Defects and Failures in Pressure Vessels and Piping*. Robert E Krieger Publishing Company.

28. **Ulrich, Geal D,** 1984. *A Guide to Chemical Engineering Process Design and Economics.* John Willey & Sons.

29. **Wintle, JB,** 2004. *Pressure System Casebook Causes and Avoidance of Failures and Defects.* Professional Engineering Publishing.

30. **Widera, G.E.O.,** 1982. *Pressure Vessel Design.* The American Society of Mechanical Engineers.

9 APPENDICES

UNIVERSITEIT VAN PRETORIA
UNIVERSITY OF PRETORIA
YUNIBESITHI YA PRETORIA

sasol
reaching new frontiers

Project Technical Specifications Questionnaire

Keith Johnston

Background

- **As part of Research Dissertation**

  "The Impact That Project Technical Specifications have on the Life Cycle Costs of Distillation Columns In Petrochemical Facilities "

- **Technical Requirement vs Technical Integrity**

  Requirements incl SASOL Specification and Mech and Piping Requirements (MPR)

- **Expert Opinion**

  rate technical requirement according to effect on vessel technical integrity

Example

SPECIFICATION REQUIREMENT	Has Extreme effect 5	Has Important effect 4	Somewhat Affects 3	Little Effect 2	No Effect 1	No Comment 0
The use of the ASME Code to design columns as opposed to other codes of construction	■	□	□	□	■	■

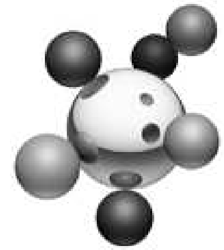
Logistics

- *Controlled Questionnaire*
- *Martie – Sasolburg*
  Marieta - Secunda
- *Due by 30 June 2005*
- *Should not take longer 20mins*

UNIVERSITEIT VAN PRETORIA
UNIVERSITY OF PRETORIA
YUNIBESITHI YA PRETORIA

sasol
reaching new frontiers

THANK YOU



Technical Questionnaire

THE CORRELATION BETWEEN SASOL TECHNICAL SPECIFICATIONS FOR DISTILLATION COLUMNS AND TECHNICAL INTEGRITY OVER THE LIFE CYCLE OF VESSEL

AS PART OF RESEARCH DISSERTATION:

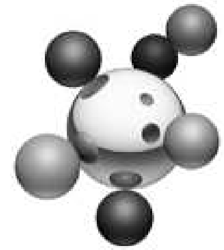
THE IMPACT PROJECT TECHNICAL SPECIFICATIONS HAVE ON THE LIFE CYCLE COSTS OF DISTILLATION COLUMNS IN PETROCHEMICAL FACILITIES

BY: Keith Johnston

June 2005

sasol
reaching new frontiers

UNIVERSITEIT VAN PRETORIA
UNIVERSITY OF PRETORIA
YUNIBESITHI YA PRETORIA



Instructions for Completing Questionnaire

Section 1 of the questionnaire should be completed in full.

The rest of the questionnaire is to be completed as far as the expert sees fit i.e. there might be questions/sections that you feel are not appropriate to answer, please indicate this by marking the "0" column.

Section 2 of the questionnaire is with regards to ***design*** and ***constructability*** requirements per SASOL specification.
Section 3 of the questionnaire is with regards to ***material selection*** and ***quality*** requirements per SASOL specification.
Section 4 of the questionnaire is with regards to ***welding*** requirements per SASOL specification.

Sections 2, 3, and 4 are based on rankings of the specification requirements in terms of how much the expert sees the requirement affecting vessel technical integrity. The rankings are as follows:

Ranking of 5	-	Has an ***extreme*** affect on vessel technical integrity
Ranking of 4	-	Has an ***important*** affect on vessel technical integrity
Ranking of 3	-	Has ***somewhat*** of an affect on vessel technical integrity
Ranking of 2	-	Has ***little*** affect on vessel technical integrity
Ranking of 1	-	***Does not*** affect on vessel technical integrity
Ranking of 0	-	not within my field of expertise

Complete the sections by ticking the rating you feel is most appropriate and feel free to add specification requirements not listed in the questionnaire, which you feel affect the integrity of the vessel over its life cycle, in the "other" section. Comments on specific requirements are welcome and can be completed in the comments section.

Questionnaires to be completed and returned by 30 JUNE 2005

UNIVERSITEIT VAN PRETORIA
UNIVERSITY OF PRETORIA
YUNIBESITHI YA PRETORIA

Introduction

The research, for which this survey forms part, is aimed at establishing the correlation between SASOL ***specification requirements*** (that include requirements from both the Sasol Specifications and the Mechanical and Piping Requirements (MPR)) and ***Life Cycle Costs*** (LCC) for vessels. Distillation columns have been chosen because of the apparent high acquisition costs for such equipment.

The intent of the project is to

i) obtain data on SASOL specification requirements applicable to distillation columns

ii) gather data regarding the total cost of ownership of such vessels

This questionnaire is focused on part i) i.e., gathering information regarding SASOL specification requirements for vessels.

Section 1: Participant Profile

Name: ____________________________________

Designation/Responsibility: ____________________________________

Division (e.g. Maintenance, QA, Welding etc.): ____________________________________

Number of years SASOL experience (please circle):

(1) 1-5 (2) 6-10 (3) 11-20 (4) 20+

UNIVERSITEIT VAN PRETORIA
UNIVERSITY OF PRETORIA
YUNIBESITHI YA PRETORIA

Section 2: Design and Constructability Specifications Requirements

A ranking of 1 being "***no effect on vessel integrity***" and a ranking of 5 "***having an extreme affect on vessel technical integrity***".

Technical Integrity being defined as:

"The assurance that, under specified operating conditions, there is no foreseeable risk of equipment failure that will endanger the safety of personnel, the environment, or adversely affect the business value of an asset"[1]

SPECIFICATION REQUIREMENT	Has Extreme effect 5	Has Important effect 4	Somewhat Affects 3	Little Effect 2	No Effect 1	No Comment 0
1. The use of the ASME Code to design columns as opposed to other codes of construction	☐	☐	☐	☐	☐	☐
2. The use of ASME VIII Div 1 as opposed to ASME VIII Div 2 for design	☐	☐	☐	☐	☐	☐
3. Standard tabulated piping loads applied to vessel nozzles (tabulated values)	☐	☐	☐	☐	☐	☐
4. The use of 2:1 semi-ellipsoidal heads	☐	☐	☐	☐	☐	☐
5. Torispherical heads NOT being allowed on columns with an L/D ratio equal to or greater than 10	☐	☐	☐	☐	☐	☐
6. The use of hemispherical heads of crown plate and petal design	☐	☐	☐	☐	☐	☐
7. Permanent internal/external attachments NOT allowed on knuckle areas of heads	☐	☐	☐	☐	☐	☐
8. Nozzle attachment to shell weld to be full penetration through neck to outside of shell for nozzles 3" larger	☐	☐	☐	☐	☐	☐
9. SASOL Category 1 and 2 columns to have integrally reinforced nozzles	☐	☐	☐	☐	☐	☐
10. Cyclic loaded vessels to have lip type forgings	☐	☐	☐	☐	☐	☐
11. Bolts and nuts on nozzle flanges must be removable towards the vessel	☐	☐	☐	☐	☐	☐
12. Weld build-up for skirt to head attachment weld (non-slender[2] vessels)	☐	☐	☐	☐	☐	☐
13. Y-forging for skirt to head attachment (Slender vessels)	☐	☐	☐	☐	☐	☐
14. Skirt to shell junction to be fatigue resistant (Slender vessels)	☐	☐	☐	☐	☐	☐
15. Internal flanges to be at least B16.5 150# double welded slip-on type	☐	☐	☐	☐	☐	☐

[1] Professor J. Amadi-Echendu
[2] Slender vessel: L/D ratio greater than 12

16. Column overhead structure to be drawn off the cylindrical section of the column shell instead of from the crown of the head.	☐	☐	☐	☐	☐	☐
OTHER						
17.	☐	☐	☐	☐	☐	☐
18.	☐	☐	☐	☐	☐	☐
19.	☐	☐	☐	☐	☐	☐

COMMENTS ON SPECIFIC REQUIREMENTS:

____

____

____

____

____

____

____

____

____

Section 3: Material Selection and Quality Specification Requirements (Generally Based on Category 2 Vessel Requirements)

Technical Integrity being defined as:

"The assurance that, under specified operating conditions, there is no foreseeable risk of equipment failure that will endanger the safety of personnel, the environment, or adversely affect the business value of an asset"

SPECIFICATION REQUIREMENT	Has Extreme effect 5	Has Important effect 4	Somewhat Affects 3	Little Effect 2	No Effect 1	No Comment 0
1. Corrosion allowance of 3mm on carbon steel vessels if not specified otherwise	☐	☐	☐	☐	☐	☐
2. Formed heads to be stress relieved	☐	☐	☐	☐	☐	☐
3. Intergranular Corrosion Testing on austenitic stainless steel plate material	☐	☐	☐	☐	☐	☐
4. All attachments to the shell should be of the same material specification as the shell	☐	☐	☐	☐	☐	☐
5. Dissimilar materials and welds are not allowed in process services	☐	☐	☐	☐	☐	☐
6. Maximum carbon content for carbon steels to be 0,25%	☐	☐	☐	☐	☐	☐
7. All austenitic stainless steels to be supplied in the solution annealed condition	☐	☐	☐	☐	☐	☐
8. Austenitic stainless steels in corrosive service shall be of the low carbon or stabilised grades	☐	☐	☐	☐	☐	☐
9. Vessel material in Sasol Low Temperature Service (NOT Code) to be impact tested i.e. between 0^{o}C and 15^{o}C	☐	☐	☐	☐	☐	☐
10. Recertification of base material (pre-fabricated parts) if hot formed	☐	☐	☐	☐	☐	☐
11. UT of base material (pre-fabricated parts) both hot and cold formed if fibre elongation exceeds 5%	☐	☐	☐	☐	☐	☐
12. 3.1 C certification for custom made forgings	☐	☐	☐	☐	☐	☐
13. Intermediate Stress Relieving for carbon steel components with fibre elongation > 5% and stainless steel with FE> 18%	☐	☐	☐	☐	☐	☐
14. Radiography on welds prior to PWHT	☐	☐	☐	☐	☐	☐
OTHER						
15.	☐	☐	☐	☐	☐	☐
16.	☐	☐	☐	☐	☐	☐

COMMENTS ON SPECIFIC REQUIREMENTS:

Section 4: Welding Specification Requirements

Technical Integrity being defined as:

"The assurance that, under specified operating conditions, there is no foreseeable risk of equipment failure that will endanger the safety of personnel, the environment, or adversely affect the business value of an asset"

SPECIFICATION REQUIREMENT	Has Extreme effect 5	Has Important effect 4	Somewhat Affects 3	Little Effect 2	No Effect 1	No Comment 0
1. Weld toe-to-toe clearance to be greater than 50mm or 2T whichever is greater	☐	☐	☐	☐	☐	☐
2. Load bearing attachment welds to the shell to be full penetration welds	☐	☐	☐	☐	☐	☐
3. Weld finish to be fatigue finish for welds in cyclic service	☐	☐	☐	☐	☐	☐
4. Simulated PWHT required (other than code) on plate, piping, custom made forgings and standard fittings (ITP02-1)	☐	☐	☐	☐	☐	☐
5. Vessel material in Sasol Low Temperature Service (NOT Code) to be PWHT	☐	☐	☐	☐	☐	☐
6. PWHT required for vessels in Amine service	☐	☐	☐	☐	☐	☐
7. When attachment welds cross shell weld seams the weld seam is to be ground flush 50mm either side of the attachment with 100% RT and MT/PT done prior welding the attachement	☐	☐	☐	☐	☐	☐
8. Austenitic stainless steels in corrosive service shall be of the low carbon or stabilised grades	☐	☐	☐	☐	☐	☐
OTHER						
9.	☐	☐	☐	☐	☐	☐
10.	☐	☐	☐	☐	☐	☐

COMMENTS ON SPECIFIC REQUIREMENTS:

Section 5: Other Specification Requirements

Please include any other important specification requirements which in your opinion affect the technical integrity of the vessel over the life cycle.

SPECIFIC REQUIREMENTS: