THE RECONCILIATION OF THE MATERIAL BALANCE OF A NATURAL GAS PROCESSING PLANT

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ABSTRACT

Accurate material balances serve as essential tools for controlling, evaluating and optimising petrochemical processes. In natural gas processing plants, where there are only phase separation processes and no chemical reactions, accurate material balances are crucial for ensuring the optimal processing of the natural gas hydrocarbons.

Due to random and gross errors, caused by faulty or miscalibrated instrumentation, wrong sampling methods and erroneous laboratory analyses, measured data are unreliable and unsuitable for material balances.

In order to compensate for incorrect measured variables, data reconciliation is required, to satisfy the constraints of the material balance and minimise the residual error between the measured and the adjusted variables.

Although many software packages exist that do data reconciliation, this work used Microsoft Excel®, to perform material balance reconciliation on Sasol's natural gas processing plant at Temane, because it is the most widely used engineering tool in the petrochemical industry.

A literature study was done and mathematical techniques for the reconciliation of plant data, and statistical methods to verify the results, were obtained.

Spreadsheets were created in Microsoft Excel®, to: process raw input data; derive correction coefficients from historic data; conduct steady-state testing; eliminate gross errors; reconcile the material balance, and verify the results via a sensitivity analysis.

This work was implemented and is presently being used to reconcile the material balance of the natural gas processing plant at Temane.

UITTREKSEL

Akkurate materiaalbalanse dien as noodsaaklike hulpmiddels om petrochemiese prosesse te beheer, evalueer en te optimiseer. In natuurlike gas-verwerkingsaanlegte, waar net faseskeidingsprosesse en geen chemiese reaksie-prosesse plaasvind nie, is akkurate materiaalbalanse noodsaaklik vir die optimale verwerking van die natuurlike gas-koolwaterstowwe.

Vanwee lukrake en konstante metingsfoute, soos misgekalibreerde instrumentasie, verkeerde meet- en analisemetodes, is gemete data onbetroubaar en onvoldoende vir gebruik in materiaalbalanse.

Datarekonsiliasie word benodig om vir hierdie onakkurate, gemete veranderlikes te kompenseer, deur aan die materiaalbalansbeperkings te voldoen en die fout tussen die gemete en die gerekonsilieerde data te minimeer.

Alhoewel daar baie sagtewarepakkette bestaan wat materiaalbalansrekonsiliasie doen, is daar besluit om materiaalbalansrekonsiliasie te doen vir Sasol se natuurlike gas-verwerkingsaanleg in Temane, met behulp van Microsoft Excel®, omdat dit die mees gebruikte ingenieurshulpmiddel in die petrochemiese bedryf is.

'n Literatuurstudie was gedoen om wiskundige en statistiese tegnieke te bekom, waarmee data rekonsiliasie en die verifiëring van die gerekonsilieerde aanlegdata gedoen kon word.

Sigblaaie is in Microsoft Excel® geskep, om: rou invoerdata te verwerk; korreksiekoëffisiënte van historiese data af te lei; gestadigde toestand toetsing te doen; ruwe foute te elimineer; materiaalbalans-rekonsiliasie te doen, en die resultate te verifieer deur 'n sensitiwiteitsanalise.

Hierdie werk is geïmplementeer en word huidiglik gebruik om die materiaalbalans van die natuurlike gas-verwerkingsaanleg in Temane te rekonsilieer.

ACKNOWLEDGEMENTS

I want to thank SASOL for the opportunity to pursue this Masters study, as well as my wonderful colleagues at the Temane plant for sharing their years of operational experience with me. I also want to thank my study leader Dr. Campbell for his support and guidance.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

NOMENCLATURE

Notation:

A	Cross sectional area of orifice (m^2)
C	Discharge coefficient
c	Speed of sound in fluid (m/s)
D	Distance between two electrodes (m)
F	Volumetric flow rate at normal conditions of 101.325 kPa and 273.15 K (Nm^3/h)
k	Specific heat ratio
L	Distance between transducers (m)
m_i	Measured value of i-th measured variable
$\overline{m}_i$	Reconciled value of i-th measured variable
N	Number of turns of coil
q_1	Volumetric rate of discharge measured at upstream pressure and temperature (m^3/s)
R	Ratio of variance
S_i	Mean absolute deviation of i-th measured variable
SS_p	Steady-state condition of process
t	Time (s)
V	Flow velocity (m/s)
w_i	Weight factor for m_i
X	Process variable
X_f	Filtered value of X
Y	Expansion factor

Subscripts & Superscripts:

f	Filtered value
i	Stream number
j	Unit or node number
k	Time sampling index

Greek Letters:

α	Level of significance
β	Ratio of orifice diameter to pipe diameter
$\delta^2_{f,i}$	Filtered value of an estimate of the mean square deviation
$\delta^2_{f,i-1}$	Previous filtered value of an estimate of the mean square deviation
ΔV	Inventory change
ϕ	Magnetic flux (V.s)
λ	Filter factor
μ_i	Mean of a set of data
$\upsilon^2_{f,i}$	Filtered value of an estimate of the mean square deviation
$\upsilon^2_{f,i-1}$	Previous filtered value of an estimate of the mean square deviation
ρ	Density (kg/m^3)
σ	Standard deviation

Abbreviations:

Cond	Liquid hydrocarbons / natural gas liquids / gas condensate
FG	Fuel gas
HP	High pressure
LP	Low pressure
NG	Natural gas

CHAPTER 1

INTRODUCTION

1.1 BACKGROUND

SASOL's natural gas processing plant at Temane in Mozambique produces 120 PJ of natural gas per year. Most of the gas is send to South Africa via an 866 km pipeline, while a portion of the raw gas is used for fuel gas. The fuel gas is used for heating, electricity generation and to drive the high pressure compressor turbines. The remainder of the gas is flared.

1.2 MOTIVATION

Optimisation exercises are in progress to increase the overall efficiency of the plant, by increasing the amount of export gas, and decreasing the amount of flared gas. In order to conduct optimisation exercises, accurate material balances are required.

1.3 PROBLEM STATEMENT

Due to incorrect sampling methods, faulty or bias instrumentation, and erroneous laboratory analyses, measured data are unreliable and unsuitable for material balances. In order to compensate for incorrect measured variables, data reconciliation is required, to satisfy the constraints of the material balance.

1.4 PURPOSE OF RESEARCH

The purpose of this work was to develop a reconciled material balance for SASOL's natural gas processing plant at Temane. Although there are many software packages that do data reconciliation, the author chose to use *Microsoft Excel*, to process and reconcile the material balance data, because it is the most widely used engineering tool in the petrochemical industry.

1.5 SCOPE OF WORK

In order to achieve this, the following work was done:

- A literature study was done to obtain mathematical techniques for the reconciliation of plant data, and statistical methods to verify the results.
- Spreadsheets were created in *Microsoft Excel*, to: process raw input data; derive correction coefficients from historic data; conduct steady-state testing; eliminate gross errors; reconcile the material balance, and verify the results via a sensitivity analysis.

1.6 OVERVIEW OF DISSERTATION

This dissertation describes the theory behind, the procedures involved, and the results obtained for reconciling the material balance of SASOL's natural gas processing plant at Temane.

The work is divided into 5 chapters:

Chapter 1 sets out the background, motivation, problem statement, purpose, and scope of work of the research project, as well as an overview of the dissertation. Chapter 2 introduces the reader to the nature and origin of natural gas, the workings of flow meters, and gives a thorough exposition of the theory behind data reconciliation. Chapter 3 describes the plant, the associated flow meters, and the procedure used to reconcile the material balance data, respectively. Chapter 4 discusses the results obtained for each step in the data reconciliation process, namely: the degrees of freedom analysis, data preprocessing, steady-state testing, gross error handling, material balance reconciliation, and verification of the data reconciliation results. This work ends with the conclusions reached, and the recommendations made in Chapter 5.

CHAPTER 2

LITERATURE STUDY

Chapter 2 describes the nature and origin of natural gas, the workings of flow meters, and the theory behind data reconciliation, namely: degrees of freedom analysis, data preprocessing, steady-state testing, gross error handling, data reconciliation and verification.

2.1 INTRODUCTION

According to the *Energy Information Administration* (2006), global energy demand is projected to increase by 60 percent in the next 30 years. Global oil consumption is expected to grow from 80 million barrels per day in 2003 to 118 million barrels per day in 2030. The world's total proven oil reserves are estimated at 1.293 trillion barrels (*Oil & Gas Journal*, 2005). Under these growth assumptions, less than half of the world's total proven oil reserves would be exhausted by 2030.

As these oil reserves shrink, gas reserves are becoming more and more important, as an alternative energy source to oil. The world consumed 95 trillion cubic feet of natural gas in 2003. This is projected to increase at an annual average rate of 2.4% (versus 1.4% for oil) to 182 trillion cubic feet in 2030 (EIA, 2006). Proven natural gas reserves, as reported by *Oil & Gas Journal* (2005), were estimated at 6112 trillion cubic feet. Most of the increases in natural gas reserves in recent years have been in the developing world, and about three-quarters of the world's natural gas reserves are found in the Middle East and Eurasia. Russia, Iran and Qatar combined accounted for about 58% of world's natural gas reserves. The remaining reserves are spread fairly evenly among other regions of the world.

In view of current and future global energy trends, SASOL has positioned itself to become a key player in the natural gas industry. As one of the first steps in getting a foothold in this lucrative market, SASOL went into a joint venture with the Mozambican government to develop and utilise the natural gas reserves found in the Temane gas fields.

After three years of operation, SASOL's Central Processing Facility at Temane, has outgrown most of its post-start-up growth pains, and is entering a more matured phase in its plant life cycle. In the first three years, most of the time was spend on problem solving and keeping the plant running. The focus now is on optimising the assets and processes of the plant.

In order to assist plant personnel in evaluating and optimising the plant, accurate material balances need to be obtained. However, due to incorrect sampling methods, faulty or biased instrumentation, and erroneous laboratory analyses, measured data are unreliable and unsuitable for material balances. In order to compensate for incorrect measured variables, data reconciliation is required, to satisfy the constraints of the material balance.

A thorough literature study is required to understand all the aspects involved in reconciling the material balance of a natural gas processing plant. This chapter describes the nature and origin of natural gas and the workings of flow meters, and expounds the theory behind material balance reconciliation, which can be divided into the following sub-headings, namely:

1. The process of reconciling plant data;
2. Degrees of freedom analysis;
3. Data preprocessing;
4. Steady-state testing;
5. Gross error handling;
6. Data reconciliation;
7. Verification of data reconciliation results;

2.2 NATURAL GAS

Natural gas is a combustible mixture of hydrocarbon gases formed from fossilised biomass. The composition of natural gas can vary widely, but consist mainly of methane. Below is the typical composition of the natural gas found in the Temane gas field:

Component	Mol %
Methane	92.0
Ethane	3.00
Propane	1.50
Butane	0.50
Isobutane	0.40
Pentane	0.10
Isopentane	0.10
Hexane	0.15
Heptane	0.06
Octane	0.01
Nitrogen	2.40

Table 1: Temane natural gas composition

There are many theories explaining the origin of natural gas. The most widely accepted theory states that natural gas was formed at the basins of prehistoric river mouths, where vast amounts of alluvial sediment covered the organic remains of marine organisms, like microscopic plankton, that settled on the sea floor. This sediment layer delayed the decomposition process of the biomaterial, by preventing oxygen and living organisms, feeding off the biomaterial, from reaching it. Over time, more and more sediment, mud and other debris piled on the biomaterial, exerting pressure on the organic material. This compression, combined with high subterranean temperatures, broke down the carbon bonds in the organic material to produce simple hydrocarbon molecules, like methane, ethane and propane. At low temperatures (shallower deposits) more oil is produced relative to natural gas. At higher temperatures, more natural gas is created as opposed to oil, because more energy is available for the decomposition process. That is why natural gas is usually associated with oil in deposits that are 1 to 3 kilometres below the earth's crust. Deeper deposits usually contain natural gas, and in many cases, pure methane.

Natural gas can also be formed through the transformation of organic material by tiny micro-organisms. This type of methane is referred to as biogenic methane. Tiny methane producing micro-organisms metabolise organic material into methane and are commonly found in areas near the surface of the earth that are void of oxygen.

These micro-organisms also live in the intestines of most animals, including humans. Formation of methane in this manner usually takes place close to the surface of the earth, and the methane produced is usually lost into the atmosphere. In certain circumstances this methane gets trapped underground, which is later recovered as natural gas. An example of biogenic methane is landfill gas. Waste-containing landfills produce a relatively large amount of natural gas from the decomposition of the waste materials.

A third way in which natural gas can be formed is through abiogenic processes, where hydrogen and carbon molecules react with mineral deposits in the earth's crust, to form basic hydrocarbon molecules in the absence of oxygen (NaturalGas.org, 2004).

2.3 FLOW METERS

The readings of five types of flow meters are used in the material balance of the Temane plant: orifice plates, venturi tubes, V-cones, magnetic, and ultrasonic flow meters.

According to Perry (1988) the first three are known as pressure differential flow meters, which employ the Bernoulli Equation to measure flow. Bernoulli's Equation states that the sum of all forms of energy in a fluid along an enclosed path, like a flow line, is the same at any two points in that path, and that an increase in velocity occurs simultaneously with a decrease in pressure. These flow meters guide the flow of the fluid through a section in the pipe with a different cross sectional area than the pipe, resulting in a reduction in pressure, from which the flow velocity can be calculated.

The practical working equation for volumetric flow, adopted by the *ASME Research Committee on Fluid Meters* (2001) for use with either gases or liquids, is:

$$q_1 = CYA_2\sqrt{\frac{2g\cdot(p_1-p_2)\rho_1}{1-\beta^4}} \tag{2.1}$$

Where A_2 = cross-sectional area of throat; C = discharge coefficient; p_1, p_2 = pressure at upstream and downstream static pressure taps respectively; q_1 = volumetric rate of discharge measured at upstream pressure and temperature; Y = expansion factor; β = ratio of throat diameter to pipe diameter; ρ_1 = density at upstream pressure and temperature. For the flow of gases, expansion factor Y, which allows for the change in gas density as it expands adiabatically from p_1 to p_2, is given by:

$$Y = \sqrt{r^{2/k}\left(\frac{k}{k-1}\right)\cdot\left(\frac{1-r^{(k-1)/k}}{1-r}\right)\cdot\left(\frac{1-\beta^4}{1-\beta^4 r^{2/k}}\right)} \tag{2.2}$$

Where $r = p_2/p_1$; k = specific heat ratio (c_p/c_v); and the expansion factor Y is unity for liquid flows.

2.3.1 Orifice Plate Flow Meters

An orifice plate is a thin, flat metal plate with a circular opening, which is inserted into a pipe and placed perpendicular to the flow stream. As the flowing fluid passes through the orifice plate, the restricted cross sectional area causes an increase in velocity and corresponding decrease in pressure. The typical orifice plate has a concentric, sharp edged opening, as shown in Figure 1. The flow rate can be calculated with Equation 2.1, using the measured pressure drop across the orifice plate between the upstream pressure tap (P_1) and the pressure tap immediately downstream of the orifice opening (P_3).

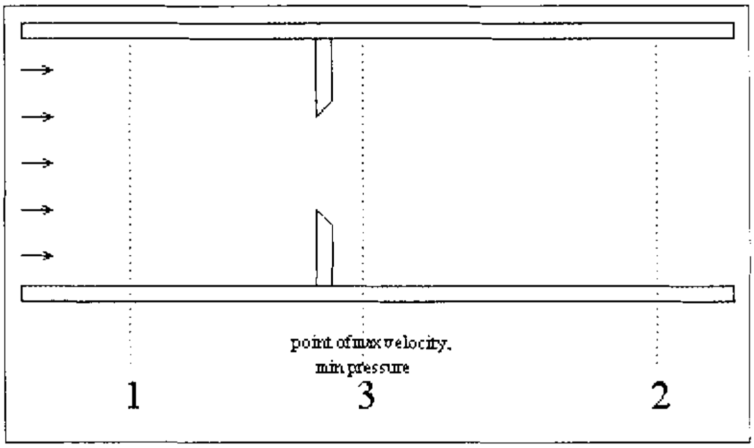


Figure 1: Flow orifice plate (Marlin, 2006)

The orifice plate is the most commonly used flow meter, because it is simple and cheap to manufacture and can be delivered for almost any application in any material, but it creates a large non-recoverable pressure drop due to the turbulence around the plate, leading to a high loss of kinetic energy. Their accuracies are poor at low flow rates and require a good shape and clean surface to achieve high accuracies. The pressure recovery is limited for an orifice plate and the permanent pressure loss depends primarily on the area ratio. For an area ratio of 0.5, the head loss is about 70 - 75% of the orifice differential. Typical accuracies lie between 2-5% of full scale (Marlin, 2006).

2.3.2 Venturi Tube Flow Meters

According to Foust (quoted by Marlin, 2006) venturi meters consist of a short length of straight tubing connected at either end to the pipe line by conical sections, where the fluid is first accelerated through converging cone of 15-20 degree angle and then slowed down in smaller diverging cone of 5-7 degree angle (Fig. 2). The change in cross sectional area causes a variance in the velocity and pressure of the flowing fluid. The pressure drop between the upstream side of the feed cylinder and the narrow cylindrical throat is measured and used to calculate the flow rate through the venturi meter.

Although more expensive than orifice plate flow meters, venturi meters provide less permanent pressure drops, and are more reliable, because their smooth geometry minimises turbulence and boundary layer separation (drag), ensuring steadier pressure signals and less energy losses.

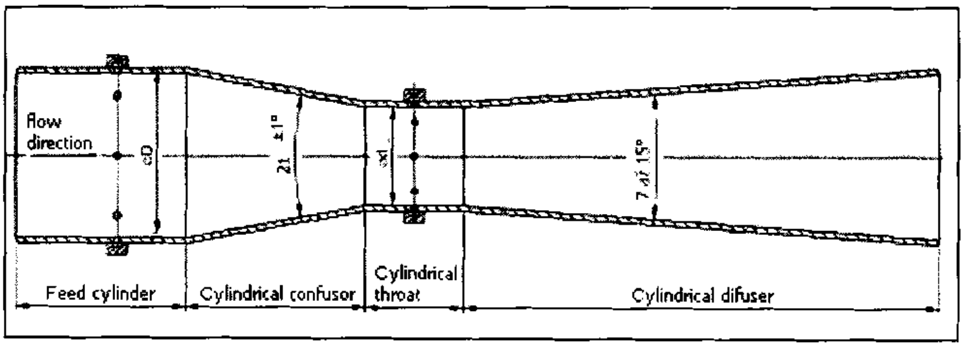


Figure 2: Venturi tube flow meter (Mattech, 2004)

High pressure and energy recovery (up to 80% of the differential pressure generated at the constricted area is recovered) makes the venturi meter suitable where only small pressure heads are available. The venturi tube is suitable for clean, dirty and viscous liquids and some slurry services. Venturi meters have typical accuracies of 1% (Marlin, 2006).

2.3.3 V-Cone Flow Meters

V-cone flow meters, according to McCrometer (2002), operate on the same physical principle as other differential pressure-type flow meters, using the principle of Bernoulli, but have a different geometry which causes the fluid to flow around the outside of a centrally located cone, as opposed to through a central opening, like a orifice plate flow meter (see Fig. 3). This rerouting forces the high velocity flow regime in the central part of the pipe to mix with lower velocity flow regime closer to the sides of the pipe, resulting in well-developed flow regime, typical of a long flow path without any obstruction or disturbances, compared to extreme turbulent regimes, caused by changes to the piping, such as elbows, valves, reductions, expansions, pumps, and tees.

V-cones also perform well at low flow rates, because their cone continues to interact with the highest velocity in the pipe, compared to other pressure differential flow meters, which lose their useful pressure drop signals at low flows.

All pressure differential flow meters generate fluctuating pressure signals. On typical orifice plate flow meters, these low frequency, high amplitude signals are the result of long vortices that form just after the orifice, which disturb the pressure drop reading. V-cone meters, on the other hand, form very short vortices around the cone, resulting in low amplitude, high frequency signals, that have a high stability.

The above-mentioned performance characteristics enables the V-cone flow meter to measure flows reliably and accurately, regardless of the condition of the flow upstream of the meter, unlike other pressure differential flow meters, with centrally located openings, which do not have well-developed flow regimes due to turbulence.

The flow around a V-cone flow meter can be calculated with a derivation of the Bernoulli equation, by incorporating the measured pressure difference between the static line pressure and the low pressure regime created downstream of the cone, which can be measured via two pressure sensing taps. One tap is placed slightly upstream of the cone, and the other is located in the downstream face of the cone.

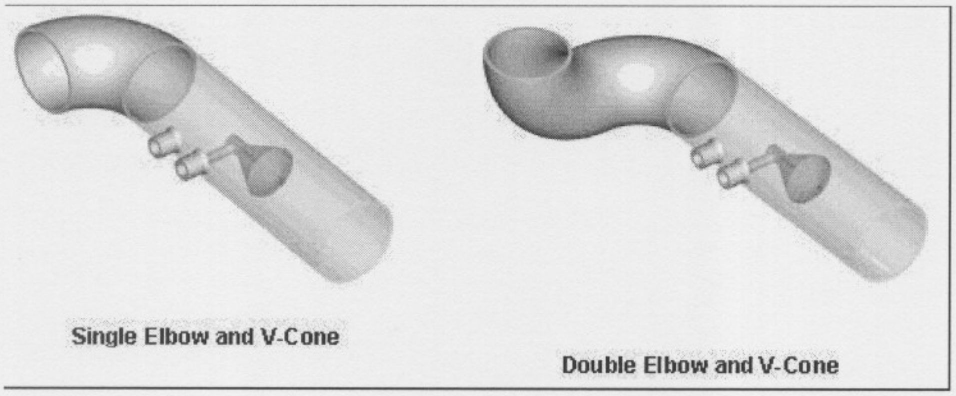


Figure 3: V-Cone flow meters (McCrometer, 2002)

V-cone flow meters have accuracies of around 0.5%. They have a lower permanent pressure loss than other pressure differential flow meters, because their signal stability allows for lower full scale pressure drop signals.

2.3.4 Magnetic Flow Meters

According to Omega Engineering (2006) magnetic flow meters operate on the basis of Faraday's Law, which states that the voltage induced across any conductor as it moves at right angles through a magnetic field is proportional to the velocity of that conductor.

$$E \propto VxBxD \quad (2.3)$$

Where E is the voltage generated in a conductor, V is the velocity of the conductor, B is the magnetic field strength, and D is the length of the conductor.

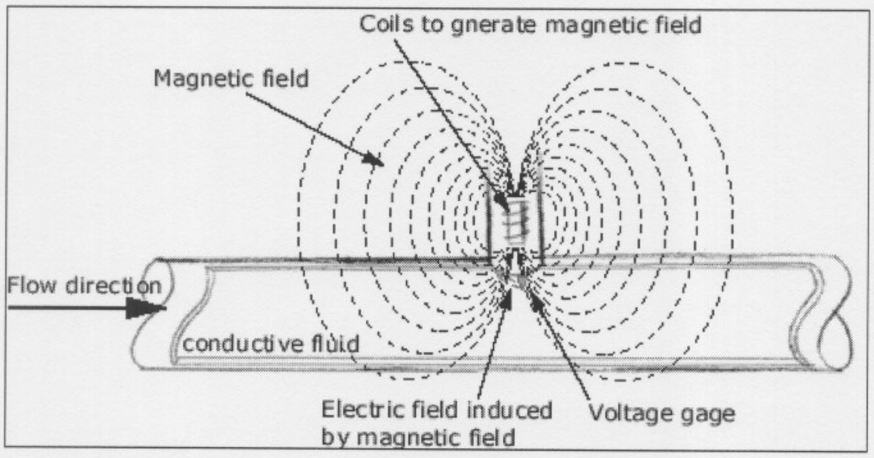


Figure 4: Magnetic flow meter (Engineering Fundamentals, 2006)

According to Faraday's law of electromagnetic induction: any change in the magnetic field with time induces an electric field perpendicular to the changing magnetic field (Engineering Fundamentals, 2006):

$$E = -N\frac{d(BA)}{dt} = -N\frac{d\Phi}{dt} \tag{2.4}$$

where E is the voltage of induced current, B is the external magnetic field, A is the cross-sectional area of the coil, N is the number of turns of the coil, ϕ = BA is the magnetic flux, and finally the negative sign indicates that the current induced will create another magnetic field opposed to the build-up of a magnetic field in the coil based on Lenz's law. When applying the above equation to magnetic flow meters, the number of turns N and the strength of the magnetic field B are fixed. Then Faraday's law becomes

$$E = -NB\frac{dA}{dt} = -NB\frac{dl}{dt}D = -NBVD \tag{2.5}$$

where D is the distance between the two electrodes (the length of conductor), and V is the flow velocity. If we combine all fixed parameters N, B, and D into a single factor, we have

$$V = \frac{E}{K} \tag{2.6}$$

Magnetic flow meters are ideal for conductive liquids, like water or aqueous solutions, but not for distilled water, non-aqueous solutions or hydrocarbons. Magnetic flow meters have accuracies in the range of 1 to 2% and are ideal for applications where low pressure drops and minimal maintenance are required.

2.3.5 Ultrasonic Flow Meters

According Engineering Fundamentals (2006) ultrasonic flow meters determine the flow velocity of a stream, by measuring the travelling time or the frequency shift of ultrasonic waves in a pre-configured acoustic field crossing the fluid flow. A pair of transducers, each having its own transmitter and receiver, is placed on the pipe wall, one on the upstream and the other on the downstream side. The time for the acoustic waves to travel from the upstream transducer to the downstream transducer (t_d) is shorter than the time it requires for the same waves to travel from the downstream to the upstream (t_u) transducer.

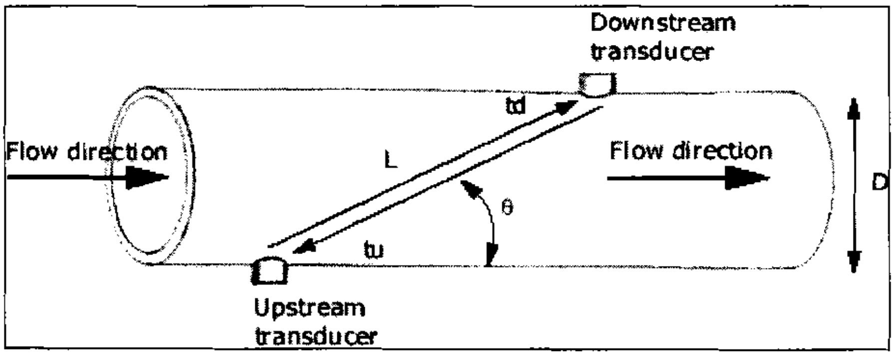


Figure 5: Ultrasonic flow meter (Engineering Fundamentals, 2006)

t_d and t_u can be expressed in the following forms:

$$t_d = \frac{L}{c + V\cos\theta} \tag{2.7}$$

$$t_u = \frac{L}{c - V\cos\theta} \tag{2.8}$$

where c is the speed of sound in the fluid, V is the flow velocity, L is the distance between the transducers and θ is the angle between the flow direction and the line formed by the transducers.

The difference of t_d and t_u is

$$\Delta t = t_u - t_d = \frac{L}{c - V\cos\theta} - \frac{L}{c + V\cos\theta} = \frac{2VL\cos\theta}{c^2 - V^2\cos^2\theta} = \frac{\dfrac{2VX}{c^2}}{1 - \left(\dfrac{V}{c}\right)^2 \cos^2\theta} \tag{2.9}$$

where X is the projected length of the path along the pipe direction ($X = L\cos\theta$).

Assuming the flow velocity V is much smaller than the speed of sound c,

$$V << c \Rightarrow \left(\frac{V}{c}\right)^2 \approx 0 << 1 \tag{2.10}$$

delivers,

$$\Delta t \approx \frac{2VX}{c^2} \tag{2.11}$$

or,

$$V = \frac{c^2 \Delta t}{2X} \tag{2.12}$$

It is desirable to express c in terms of the transit times t_d and t_u to avoid frequent calibrations:

$$c + V\cos\theta = \frac{L}{t_d} \tag{2.13}$$

$$c - V\cos\theta = \frac{L}{t_u} \tag{2.14}$$

The speed of sound c becomes

$$c=\frac{1}{2}\left[L\left(\frac{1}{t_d}+\frac{1}{t_u}\right)\right]=\frac{(t_d+t_u)}{t_d t_u}\frac{L}{2} \tag{2.15}$$

The flow velocity is now only a function of the transducer layout (L, X) and the measured transit times t_u and t_d:

$$V=\frac{c^2\Delta t}{2X}=\left[\left(\frac{(t_u+t_d)}{t_u t_d}\frac{L}{2}\right)\right]^2\frac{\Delta t}{2X}=\frac{L^2}{8X}\left(\frac{t_u+t_d}{t_u t_d}\right)^2\Delta t=\frac{L^2}{8X}\left[\frac{(t_u+t_d)^2(t_u-t_d)}{t_u^2 t_d^2}\right] \tag{2.16}$$

The above formula can be further simplified by utilising the following approximation:

$$(t_u+t_d)^2=4\left(\frac{t_u+t_d}{2}\right)\left(\frac{t_u+t_d}{2}\right)=4\left(t_u-\frac{\Delta t}{2}\right)\left(t_d+\frac{\Delta t}{2}\right)\approx 4t_u t_d \tag{2.17}$$

The flow velocity can therefore be written as

$$V=\frac{L^2}{8X}\left[\frac{(t_u+t_d)^2(t_u-t_d)}{t_u^2 t_d^2}\right]\approx\frac{L^2\Delta t}{2Xt_u t_d} \tag{2.18}$$

2.4 THE PROCESS OF RECONCILING PLANT DATA

The process of data reconciliation can be described by the following algorithm, which was derived from the one used by Li *et al.* (2000):

2.4.1 Degrees of Freedom Analysis

In step 1, calculate the spatial redundancy of the problem. If the spatial redundancy is negative, data reconciliation is not feasible, and new instrumentation needs to be added to measure some of the unmeasured streams.

2.4.2 Data Collection

Collect process data from the plant's distributed control system (DCS), local meters, and laboratory analyses.

2.4.3 Data Preprocessing

In step 3, data preprocessing on historic data is required to identify integral gross errors associated with the measuring instruments.

2.4.4 Steady-State Testing

The fourth step is to test the process for steady-state conditions. If the test shows steady-state conditions, then proceed to (2.4.5), else go back to (2.4.2).

2.4.5 Gross Error Handling

In step 5, gross errors are eliminated from the measured data, by correcting them with *correction coefficients*, determined from (2.4.3).

2.4.6 Data Reconciliation

Do data reconciliation in step 6, to satisfy the constraints of the material balance.

2.4.7 Verification of Data Reconciliation Results

The 7^{th} and final step in the data reconciliation process is the verification of the data reconciliation results through a sensitivity analysis.

2.5 DEGREES OF FREEDOM ANALYSIS

In order to solve the material balance of a plant, it is important to calculate the spatial redundancy of the problem, by means of a degrees of freedom analysis. If the spatial redundancy is negative, data reconciliation of the material balance is not feasible and new instrumentation need to be added to measure some of the unmeasured streams.

According to Ponting (1994), the degrees of freedom of a system can be expressed by the following equation:

$$\text{Degrees of Freedom} = \text{Equations} - \text{Unknowns} \tag{2.19}$$

For a processing plant, equation (2.19) can be rewritten as:

$$\text{Degrees of Freedom} = \text{Nodes} - \text{Unmeasured streams} \tag{2.20}$$

2.6 STEADY-STATE TESTING

According to Brown and Rhinehart (2000) steady-state conditions are a prerequisite for data reconciliation of an industrial process, and should be identified with statistical tests, because process variables are dynamic.

Cao and Rhinehart (1995) developed a method, styled after the primitive F-test type of statistic of Crow *et al.* (1955), which uses the ratio of estimated mean square deviations, the R-statistic, to indicate whether a process is at steady-state or not. If the process is at steady-state then the R-statistic will have a distribution between 0.8 and 1.4, with an average near unity. If the process is not at steady-state then the filtered value will differ from the data, and the ratio will differ from unity, exceeding the range between 0.8 and 1.4.

The R-statistic is a ratio of two estimates of mean square deviations derived from the same set of data, and is calculated as follows:

$$R = \frac{(2-\lambda_1)\upsilon^2{}_{f,k}}{\delta^2{}_{f,k}} \tag{2.21}$$

where $\upsilon^2{}_{f,k}$ is the first filtered mean square deviation estimate, $\delta^2{}_{f,k}$ is the second filtered mean square deviation estimate, and λ_1 is the filter factor.

In order to calculate the above-mentioned mean square deviation estimates, a filtered value of the process variable is required to provide an estimate of the data mean:

$$X_f = \lambda_1 X_k + (1-\lambda_1)X_{f,k-1} \tag{2.22}$$

X = the process variable

X_f = filtered value of X

λ_1 = filter factor

k = time sampling index

The first estimate of the mean square deviation is an exponentially weighted moving deviation which is based on the difference between the data and the average:

$$\upsilon^2_{f,k} = \lambda_2(X_k - X_{f,k-1})^2 + (1-\lambda_2)\upsilon^2_{f,k-1} \tag{2.23}$$

$\upsilon^2_{f,k}$ = Filtered value of an estimate of the mean square deviation

$\upsilon^2_{f,k-1}$ = Previous filtered value

The second estimate of the mean square deviation is an exponentially weighted moving deviation based on sequential data differences:

$$\delta^2_{f,k} = \lambda_2(X_k - X_{f,k-1})^2 + (1-\lambda_2)\delta^2_{f,k-1} \tag{2.24}$$

$\delta^2_{f,k}$ = Filtered value of an estimate of the mean square deviation

$\delta^2_{f,k-1}$ = Previous filtered value

When testing a process, SS_p, for steady-state, it is necessary to use statistical measures to filter out the effects of process noise and data outliers. The null hypothesis method can be used to accomplish the aforementioned goal. The null hypothesis states that if the computed R-statistic of a process variable, SS_i, is greater than 1.4 or less than 0.8, then we are $100(1-\alpha)$ percent confident that the process is not at steady-state. Consequently, a value of R less than 1.4 and greater than 0.8 means the process may be at steady-state. Values of either "0" or "1" are assigned to a variable, SS_i, to represents the state of the process. If R-calculated is greater than 1.4 or less than 0.8 then "reject" steady-state with $100(1-\alpha)$ confidence, and assign $SS_i = 0$. Alternately, if R-calculated lies between 0.8 and 1.4 "accept" that the process may be at steady-state, and assign $SS_i = 1$.

In expanding the before-mentioned method for analysis of multivariable processes, it can be claimed that a process is not at steady-state if any process variable is not at steady-state, and might be at steady-state if all variables might be. This can be expressed with a single statistic, where N is the total number of variables in a process:

$$SS_{process} = \prod_{i=1}^{N} SS_i \tag{2.25}$$

If the process is at steady-state:

$$P(SS_{process} = 1) = \prod_{i=1}^{N} P(SS_i = 1) = \prod_{i=1}^{N} (1 - \alpha_i) \tag{2.26}$$

$$(1 - \alpha_{process}) = \prod_{i=1}^{N} (1 - \alpha_i) \tag{2.27}$$

Use Equation (2.28) to determine the required level of significance for the steady-state identification test on each process variable in a multivariable process:

$$\alpha_i = 1 - \sqrt[N]{(1 - \alpha_{process})} \tag{2.28}$$

The R-Statistic requires that there exists no auto-correlation between data points from the same measured variable, and no cross-correlation between different measured variables. Auto-correlation between data points can be eliminated by increasing the measurement interval. Cross-correlation between two measured variables can be removed by replacing one of them with another measured variable which do not cross-correlate with the remaining one.

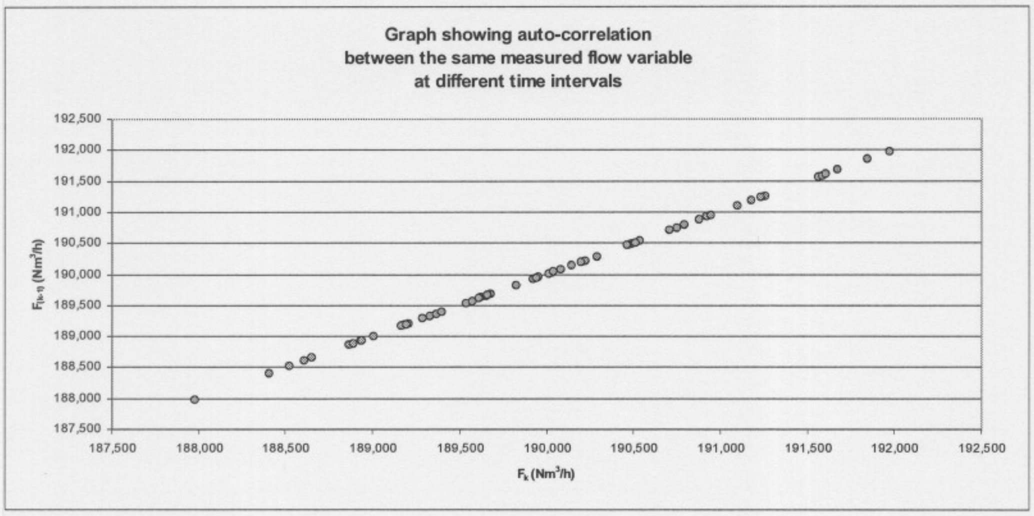


Figure 6: Graph showing auto-correlation between data from the same measured flow variable at different time intervals

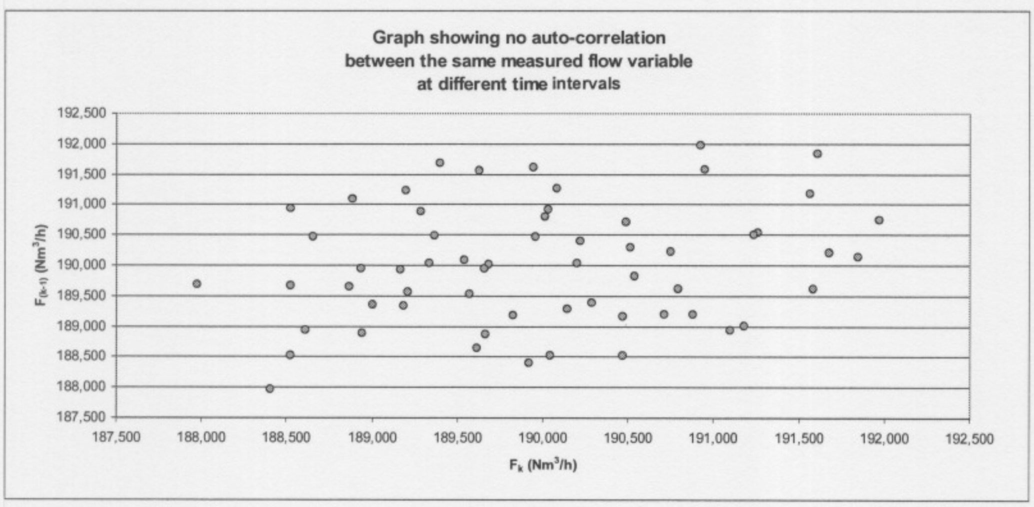


Figure 7: Graph showing no auto-correlation between data from the same measured flow variable at different time intervals

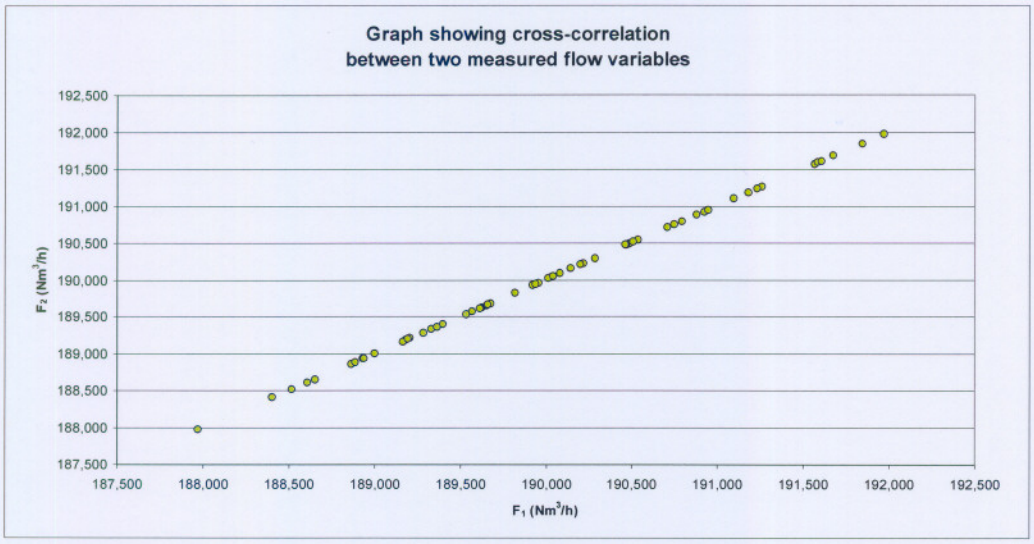


Figure 8: Graph showing cross-correlation between two measured flow variables

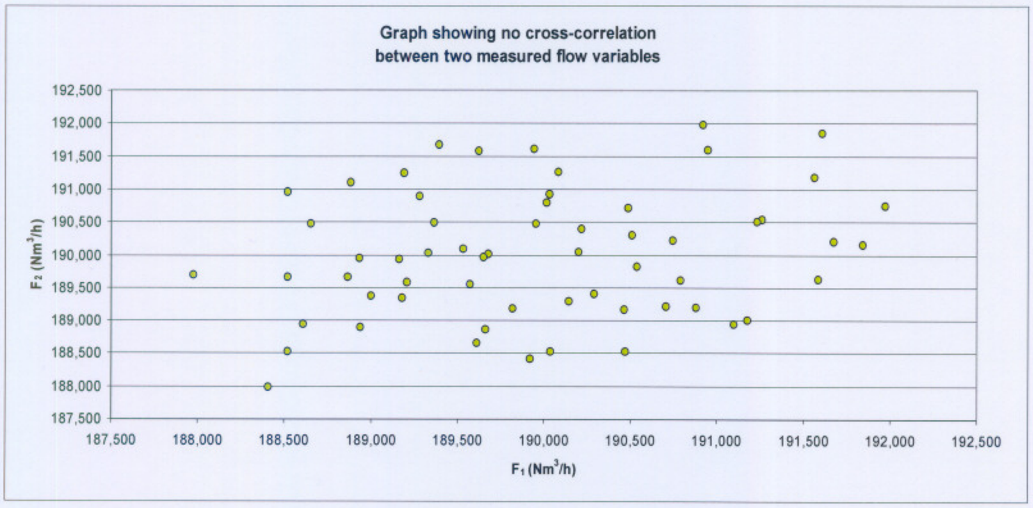


Figure 9: Graph showing no cross-correlation between two measured flow variables

2.7 GROSS ERROR HANDLING

Most data reconciliation techniques, like the *least-squares* method, require the absence of gross errors like measurement bias and outliers (Chen *et al.*, 1997).

2.7.1 Outliers

The standard deviation is very sensitive for outlying values, as it is unduly inflated, because $(x_i-\mu_i)$ is squared (Kaufman & Rousseeuw, 1990). Hartigan (1975) notes that one needs a dispersion measure that is not too sensitive to outliers. Therefore, use the *mean absolute deviation*, instead of the *standard deviation*, for the *least-squares* method:

$$S_p = \frac{1}{n}(|x_1 - \mu_1| + |x_2 - \mu_2| + \ldots + |x_n - \mu_n|) \tag{2.29}$$

where the contribution of each measurement x_i is proportional to the *absolute value* $|x_i - \mu_i|$. This measure is more robust (Hampel *et al.*, 1986), in the sense that one outlying observation will not have such a large influence on S_p.

2.7.2 Measurement Bias

The bottleneck of data reconciliation is gross error handling. The sources of gross errors include malfunctioning instruments, process leaks, non-steady-state operation, and mismatching models, etc. (Crowe *et al.*, 1996).

In many industrial cases, as shown in Figure 10, gross errors often occur as the result of measurement bias. It should be noted that gross errors exist at all measurement intervals, and not only at one measurement point. This continuous gross error is defined as a *persistent gross error* (PGE). When data reconciliation is performed on a real process, the assumption is that most of the measurement instruments, especially the flow rate instruments, have *persistent gross errors*.

Figure 10: Persistent gross error in process measurement

Gross errors materialise as nodal imbalances, where the residual of the expression

$$\Sigma \text{ Node Flows In} - \Sigma \text{ Node Flows Out} \qquad (2.30)$$

differs substantially from zero, even after proper scaling. Gross errors are typically caused by:

- Automated data entry errors (meter signal failures and biased instrumentation)
- Manual data entry errors (incorrect meter readings, laboratory analyses)

A calculated nodal imbalance in excess of a predefined tolerance, or an automated correction to a flow or movement that exceeds the meter's accuracy, are typical mathematical criteria for detecting gross errors. But according to Grosdidier (2002), material balance reconciliation is the primary means of detecting measurement discrepancies.

Measurement inconsistencies can be identified by statistical analysis of reconciliation results (Grosdidier, 2002). Data reconciliation makes corrections to measurements in order to minimise the sum of residuals around the nodes. If random measurement errors are truly the source of the imbalances, the daily corrections to each measurement should on average, sum to zero (Grosdidier, 1999). Stated differently, the frequency distribution diagram of the daily corrections for each measurement should be centred on the zero axis (see continuous green line in Figure 11). Conversely, a sustained bias in the correction indicates that a non-random process is at hand, which might suggest a faulty or biased measurement. The latter is illustrated by the red curve in Figure 11, which shows that a total of 27 daily measurements of a particular flow meter were corrected by 1%.

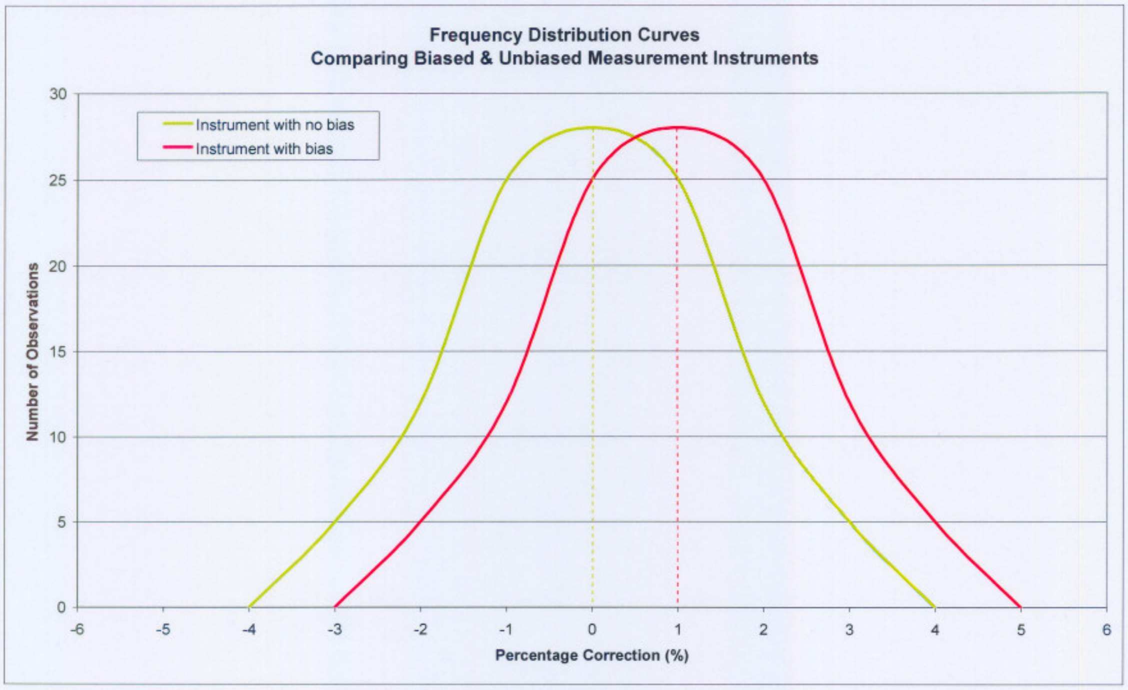


Figure 11: Frequency distribution curves comparing biased and unbiased instruments

2.7.3 Correction Coefficients

Correction coefficients are factors used to eliminate gross errors from measured data. They are calculated with the following equation:

$$\text{Correction coefficient} = (100 - \%\ \text{Bias})/100 \tag{2.31}$$

2.8 DATA RECONCILIATION

According to Van der Walt (1996) data reconciliation is the mathematical technique where process data are minimally adjusted to satisfy the constraints of a material balance. In a natural gas processing plant, where no chemical process changes occur, but only phase changes and separation occurs, data reconciliation is the mathematical technique where process variables are minimally adjusted in order to satisfy the constraints of a natural gas processing plant, where the total mass recovered from the natural gas wells are equal to the total mass processed through the plant's processing units, and equal to the total mass ending up in the product streams.

The best data reconciliation method is the mathematical technique where process data are adjusted to satisfy the constraints of a material balance, as wells as minimising the *least-squares* residual between the measured variables and the true, but unknown variables (Chen *et al.*, 1997):

$$\Re = \sum_{i=1}^{n} w_i \left(m_i - \bar{m}_i \right)^2 \tag{2.32}$$

Where w_i is the weight factor for m_i, the i-th measured data point, and $\overline{m}_i$ the reconciled data point. The reconciled $\overline{m}_i$ data points satisfy all the constraints set by the material balance. In 1970 Nielson and Diaz described a method to reconcile metallurgical balances. In equation (2.32) w_i is replaced with $w_i = k/S_i^2$ where k has a value of 0 or 1, and S_i^2 is an estimation of the error variation associated with the i-th data point. A function that uses the *weighted sum of squares* method must be minimised:

$$\Re = \left(\frac{m_1 - \overline{m}_1}{S_1} \right)^2 + \left(\frac{m_2 - \overline{m}_2}{S_2} \right)^2 + \ldots\ldots + \left(\frac{m_n - \overline{m}_n}{S_n} \right)^2 \tag{2.33}$$

The reconciled variables are obtained, where $\Re$ is as a minimum, and the constraints of the material balance are satisfied.

2.9 VERIFICATION OF RECONCILIATION RESULTS

The process of reconciling a material balance is not complete until the results are verified. According to Laguitton (1980) the reliability of the reconciliation results of a material balance can be determined through a sensitivity analysis. A sensitivity analysis is used to classify data with respect to the amount of information a data point contains. The standard deviation of a set of data is a measure of the sensitivity of the data (the smaller the value, the more sensitive the data). If the standard deviation of the reconciled data is smaller or equal to that of the measured data, then the reconciled data are reliable. A better indication of the sensitivity of a set of data is the percentage mean absolute deviation, because it minimises the effect of outliers and compensates for the difference in the median values:

Percentage mean absolute deviation = Mean absolute deviation / Median of data x 100 (2.34)

CHAPTER 3

EXPERIMENTAL

This chapter describes the natural gas processing plant at Temane, its associated flow meters, as well as the procedure followed to reconcile its material balance.

3.1 PLANT DESCRIPTION

The Central Processing Facility at Temane produces 120 PJ of natural gas per year from 12 wells, with depths ranging from 1.2 to 1.5 kilometres. Most of the gas is sent to South Africa via an 866 km pipeline, while a portion of the raw gas is used for fuel gas. The fuel gas is used for heating, electricity generation and to drive the high pressure compressor turbines. The remainder of the gas is flared. The plant (Fig. 12) consists out of the following processing steps:

- Separation
- Dehydration
- Condensation
- Compression
- Stabilisation

3.1.1 Receiving Facilities

Raw natural gas enters the plant into the *Receiving* facilities. In the first facility, the *Production Separators* (hereafter referred to as the *Separation Unit*), the gas stream is separated into a vapour phase and a liquid phase. In the second facility, the *Liquid Separators* (hereafter referred to as the *Liquid Separation Unit*), the liquid stream is separated into an aqueous and an organic phase. The aquaeous phase (hereafter referred to as *Produced Water*), containing 99% formation water and 1% hydrocarbons, is sent to a temporary storage vessel, from where it is re-injected into a dedicated well. The organic phase (hereafter referred to as *Condensate*) is sent to the *Stabilisation Unit*, from where it is sent to two temporary storage tanks, and into road tankers. The vapour fraction of the organic phase flows into the high pressure fuel gas system.

3.1.2 Gas Dehydration

Gas leaving the *Production Separators* enters the *Gas Dehydration Units,* where the wet gas is contacted with triethylene glycol (TEG) in order to reduce the water content of the gas to below 30 mg H_2O/Nm^3.

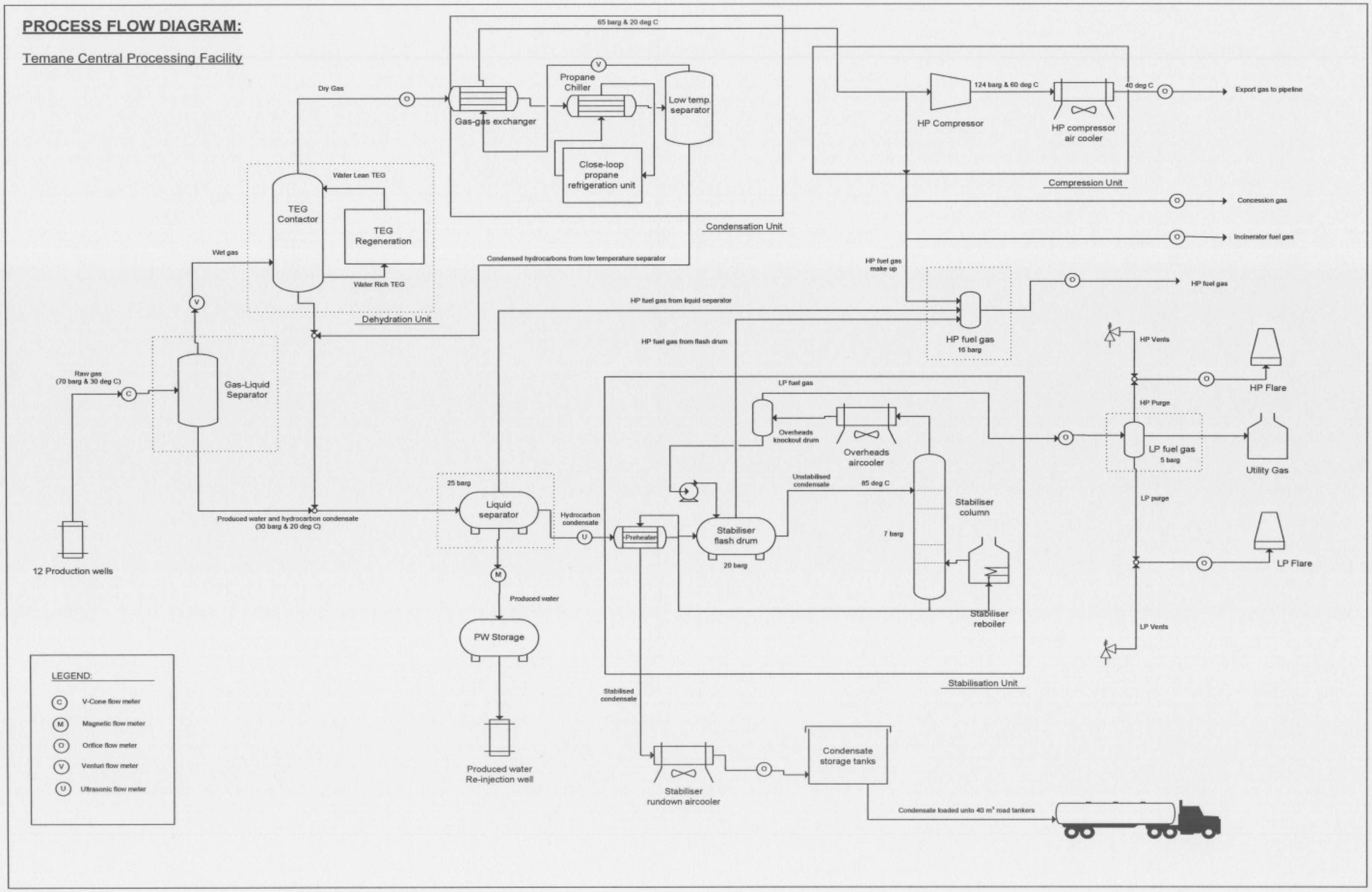


Figure 12: Flow diagram of the Temane Central Processing Facility

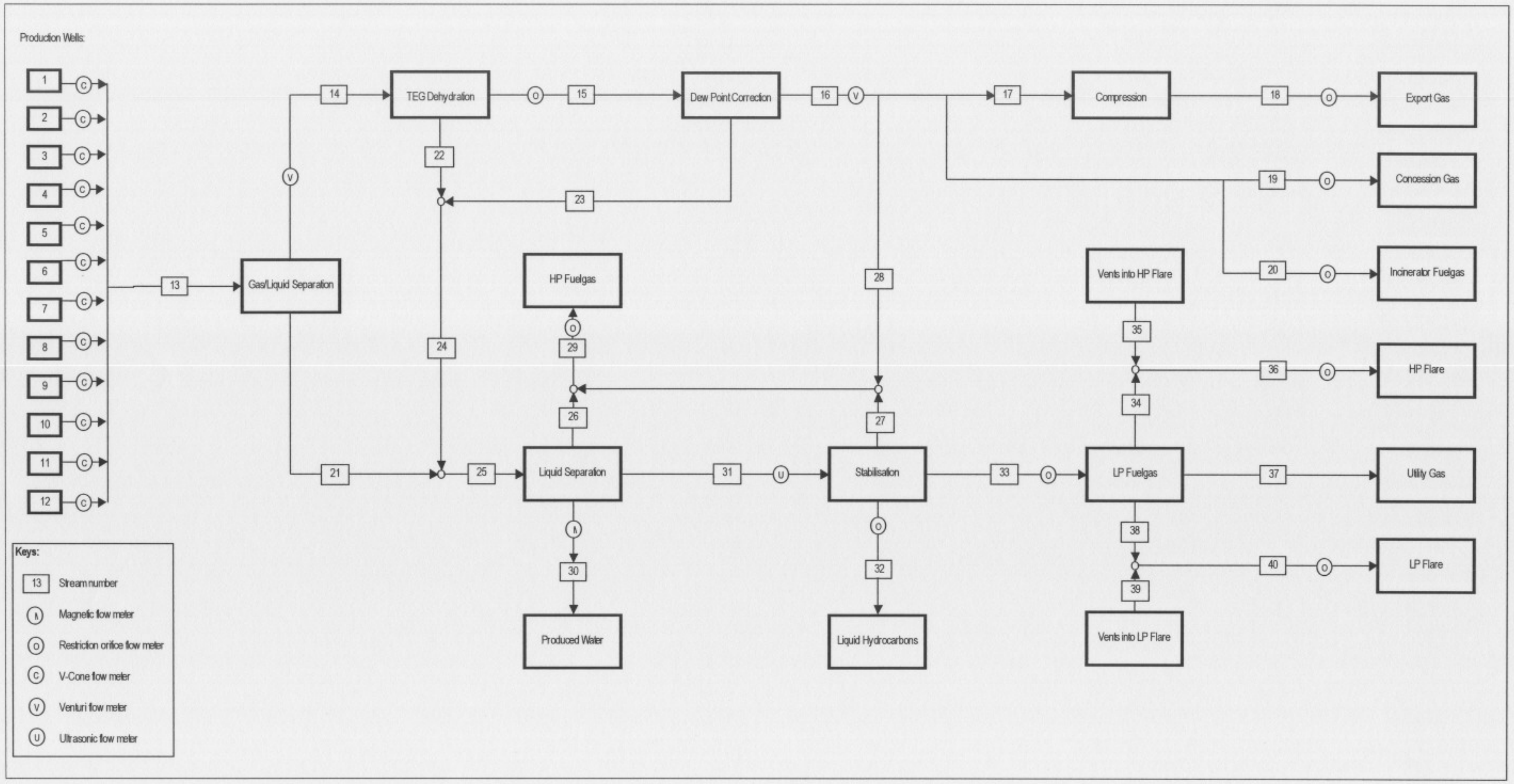


Figure 13: Simplified flow diagram of the Temane Central Processing Facility

3.1.3 Gas Dew Point Control

The *Gas Dew Point Control Units* (hereafter referred to as the *Condensation Units*) cool the dried gas to approximately 5 °C, using propane as a refrigerant, to condense and separate heavy hydrocarbons remaining in the gas. This step ensures that no condensation of hydrocarbons occur in the transmission pipeline.

3.1.4 HP Compression

The function of the *HP Compression Unit* (hereafter referred to as the *Compression Unit*) is to boost the pressure of the sales gas to 12 500 kPa (abs) before it is exported via pipeline to South Africa.

3.1.5 Concession Gas

A portion of the sales gas is sent to the Mozambican distribution line for domestic usage. Hereafter referred to as *Concession Gas*.

3.1.6 Condensate Stabilisation

The *Condensate Distillation Unit* (hereafter referred to as the *Stabilisation Unit*) produces stabilised condensate originating from the Liquid Separators, Dehydration and the Dew Point Control units. The unit is designed to produce 24 m^3/h of stabilised condensate.

3.1.7 Vent and Flare System

The Vent and Flare System collects relief and blow-down streams from the plant and associated facilities for disposal by flaring. Combustion products are subsequently discharged to atmosphere. There are separate high pressure (HP) and low pressure (LP) flare headers.

3.1.8 Fuel Gas System

The Fuel Gas System provides fuel gas at two pressure levels. High pressure (HP) fuel gas is consumed in three gas turbine electricity generators, and two high pressure gas compressor turbines, while low pressure (LP) fuel gas is consumed in fired equipment and used for purging and blanketing of vessels. Off-gas from the process units is routed to the Fuel Gas System. The balance of the fuel gas demand is provided by letting down export quality gas from the suction of the HP Compressors (hereafter referred to as *high pressure fuel gas make-up*).

3.2 DESCRIPTION OF FLOW METERS

Table 2 gives a summary of all the flow meters used in the material balance (refer to Fig. 12 for the location of these flow meters):

Stream	Description	Type	Units	Accuracy	Source
1	Temane 3	V-Cone	Nm^3/h	± 0.5%	Literature
2	Temane 4	V-Cone	Nm^3/h	± 0.5%	Literature
3	Temane 5	V-Cone	Nm^3/h	± 0.5%	Literature
4	Temane 6	V-Cone	Nm^3/h	± 0.5%	Literature
5	Temane 7	V-Cone	Nm^3/h	± 0.5%	Literature
6	Temane 9	V-Cone	Nm^3/h	± 0.5%	Literature
7	Temane 10	V-Cone	Nm^3/h	± 0.5%	Literature
8	Temane 12	V-Cone	Nm^3/h	± 0.5%	Literature
9	Temane 13	V-Cone	Nm^3/h	± 0.5%	Literature
10	Temane 14	V-Cone	Nm^3/h	± 0.5%	Literature
11	Temane 15	V-Cone	Nm^3/h	± 0.5%	Literature
12	Temane 16	V-Cone	Nm^3/h	± 0.5%	Literature
14	Dehydration Feed	Venturi Meter	Nm^3/h	± 1.0%	Literature
15	Condensation Feed	Flow Orifice	Nm^3/h	± 5.0%	Literature
16	Condensation Gas Out	Venturi Meter	Nm^3/h	± 1.0%	Literature
18	Export Gas	Compensated Flow Orifice	Nm^3/h	± 1.0%	Supplier
19	Concession Gas	Flow Orifice	Sm^3/h	± 5.0%	Literature
20	Incinerator Fuelgas	Flow Orifice	Nm^3/h	± 5.0%	Literature
29	Total HP Fuelgas	Flow Orifice	Nm^3/h	± 5.0%	Literature
30	Produced Water	Magnetic	m^3/h	± 2.0%	Literature
31	Stabiliser Feed	Ultrasonic	m^3/h	± 0.5%	Supplier
32	Stabilised Condensate	Flow Orifice	m^3/h	± 5.0%	Literature
33	LP Fuelgas	Flow Orifice	Nm^3/h	± 5.0%	Literature
36	HP Flare	Flow Orifice	Nm^3/h	± 5.0%	Literature
40	LP Flare	Flow Orifice	Nm^3/h	± 5.0%	Literature

Table 2: Summary of flow meters used for the material balance

3.3 PROCEDURE

3.3.1 Degrees of Freedom Analysis

The spatial redundancy of the problem was calculated to see whether data reconciliation was feasible.

3.3.2 Data Collection

Data was gathered via Aspen Process Explorer® from the Delta V® distributed control system (DCS) over a six-month period from 1 August 2005 to 31 January 2006. Flow sensors convert the process measurements to a milliampère signal, which is transmitted to the DCS at 30-millisecond intervals, from whence it is converted back to a flow value. This DCS data is then pulled into Excel via the add-in tool Aspen Explorer.

3.3.3 Data Preprocessing

Preliminary data reconciliation was performed on the above-mentioned collected process data, to establish the average bias of all the instruments and their respective *correction coefficients*, with which gross error handling was done.

3.3.4 Steady-State Testing

A steady-state test, using the *multivariable method*, was conducted on two hour's measured data from 00h00 to 02h00 on 16 October 2005.

3.3.5 Gross Error Handling

The *correction coefficients* obtained in step 3, were used to minimise the integral gross errors associated with the measuring instruments for the period from 01h00 to 02h00 on 16 October 2005.

3.3.6 Data Reconciliation

Data reconciliation was done on the data for the same period as (3.3.5).

3.3.7 Verification of Data Reconciliation Results

The data reconciliation results obtained from (3.3.6), were verified with a sensitivity analysis.

CHAPTER 4

RESULTS & DISCUSSION

This chapter discusses the results of all the steps taken to reconcile the material balance of the natural gas processing plant at Temane, namely: the degrees of freedom analysis, data preprocessing, steady-state testing, gross error handling, data reconciliation, and verification of the data reconciliation results.

4.1 DEGREES OF FREEDOM ANALYSIS

A *degrees of freedom analysis* delivered the following results regarding the spatial redundancy of the problem. The material balance problem comprises 15 nodes and 40 streams, of which 27 are measured. The 13 unmeasured streams were calculated via balances around the nodes.

$$\begin{aligned} \text{Degrees of freedom} &= \text{Total nodes} - \text{Unmeasured streams} \\ &= 15 - 13 \\ &= 2 \end{aligned} \tag{2.20}$$

The *degrees of freedom analysis* revealed 2 redundant variables, which over-specify the problem, and permit the reconciliation process to continue.

4.2 DATA PREPROCESSING

Preliminary data reconciliation was performed on process data from 1 August 2005 to 31 January 2006, to establish the median bias of all the instruments and their respective *correction coefficients*, with which gross error handling was done. In order to minimise the influence potential spurious occurrences, like leaks, could have on the data reconciliation process, data preprocessing was done over a wide sampling period of six months.

4.2.1 Frequency Distribution Curves

The following frequency distribution curves illustrate the level of bias on all the flow meters used in the material balance:

- Temane 3, 4, 5, 6, 7 and 9 wells
- Temane 10, 12, 13, 14, 15 and 16 wells
- Internal gas streams: dehydration feed, condensation feed & condensation gas out
- Product gas streams: export gas, concession gas and incinerator fuel gas
- HP and LP fuel gas streams
- HP and LP flare gas streams
- Liquid streams: produced water, stabiliser feed and stabilised condensate

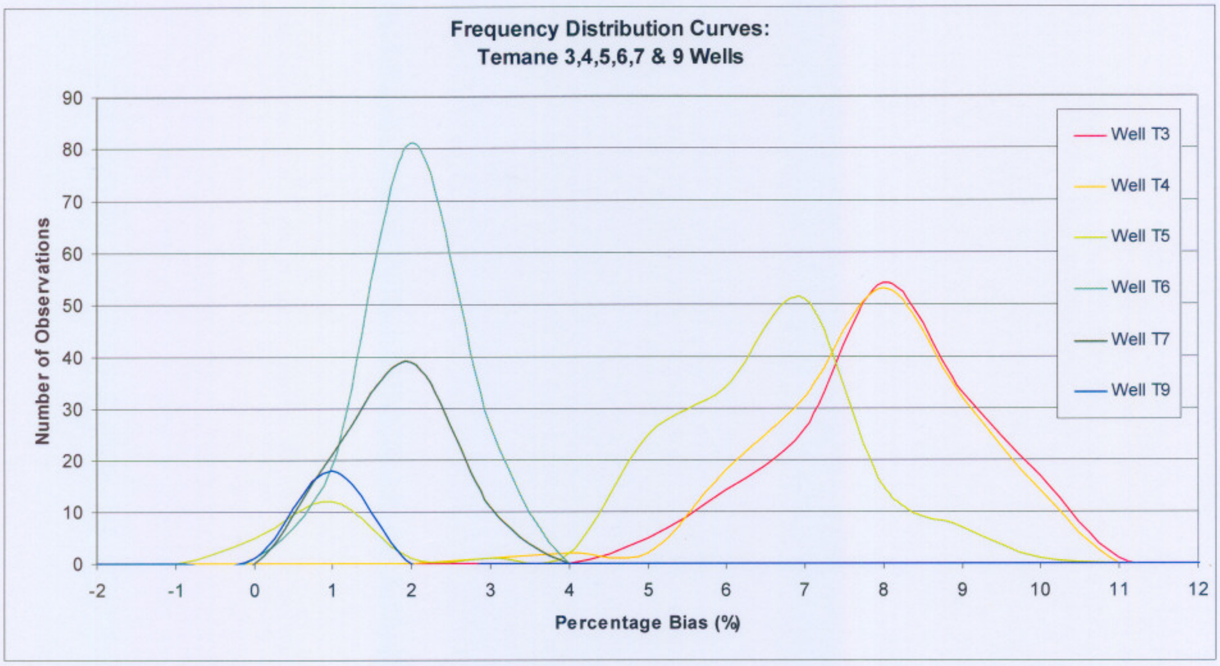


Figure 14: Frequency distribution curves of Temane 3,4,5,6,7 & 9 wells

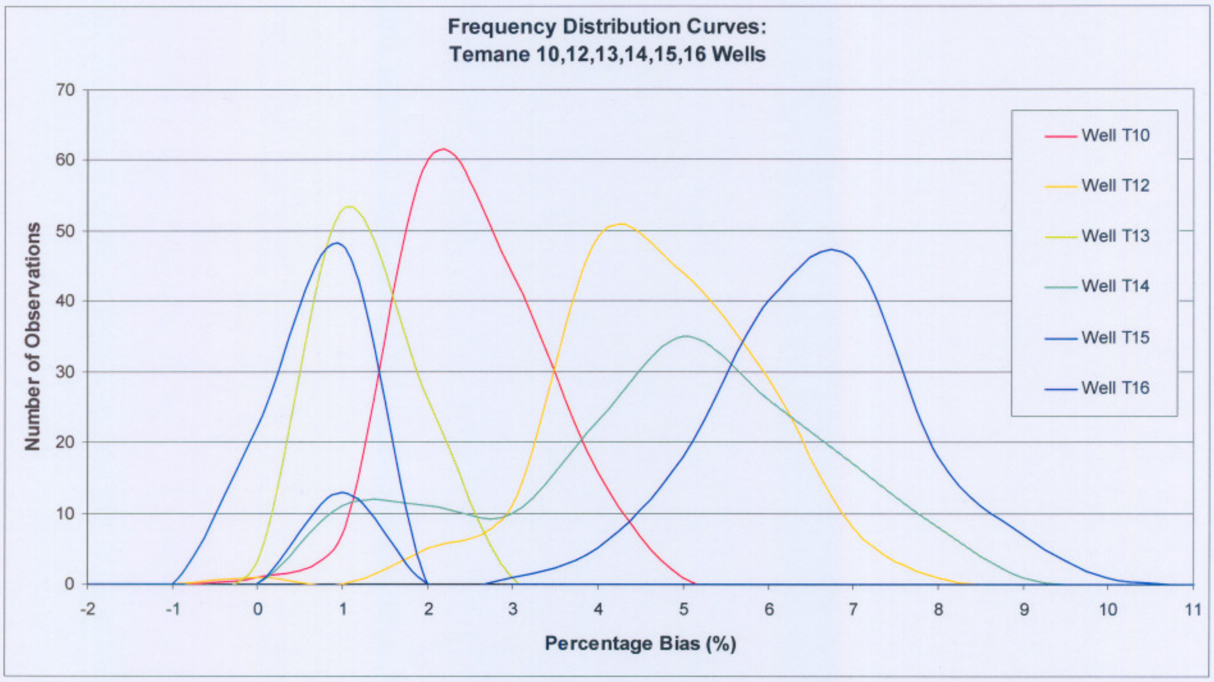


Figure 15: Frequency distribution curves of Temane 10,12,13,14,15 & 16 wells

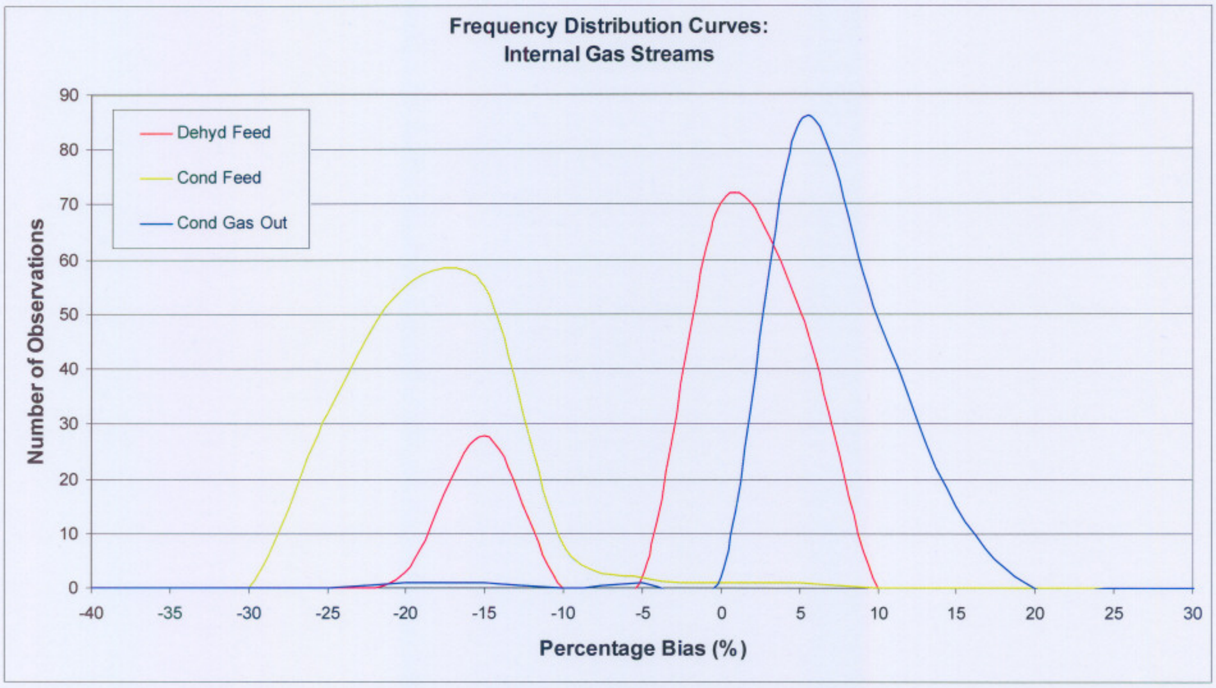


Figure 16: Frequency distribution curves of the internal gas streams

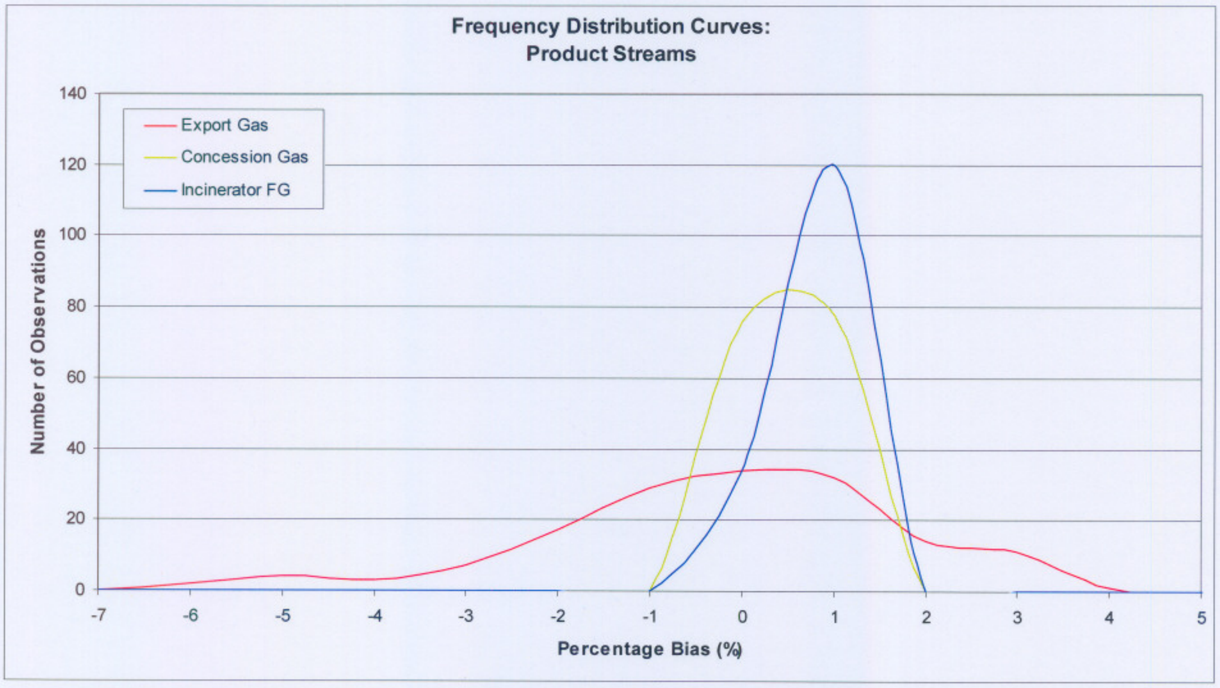


Figure 17: Frequency distribution curves of product gas streams

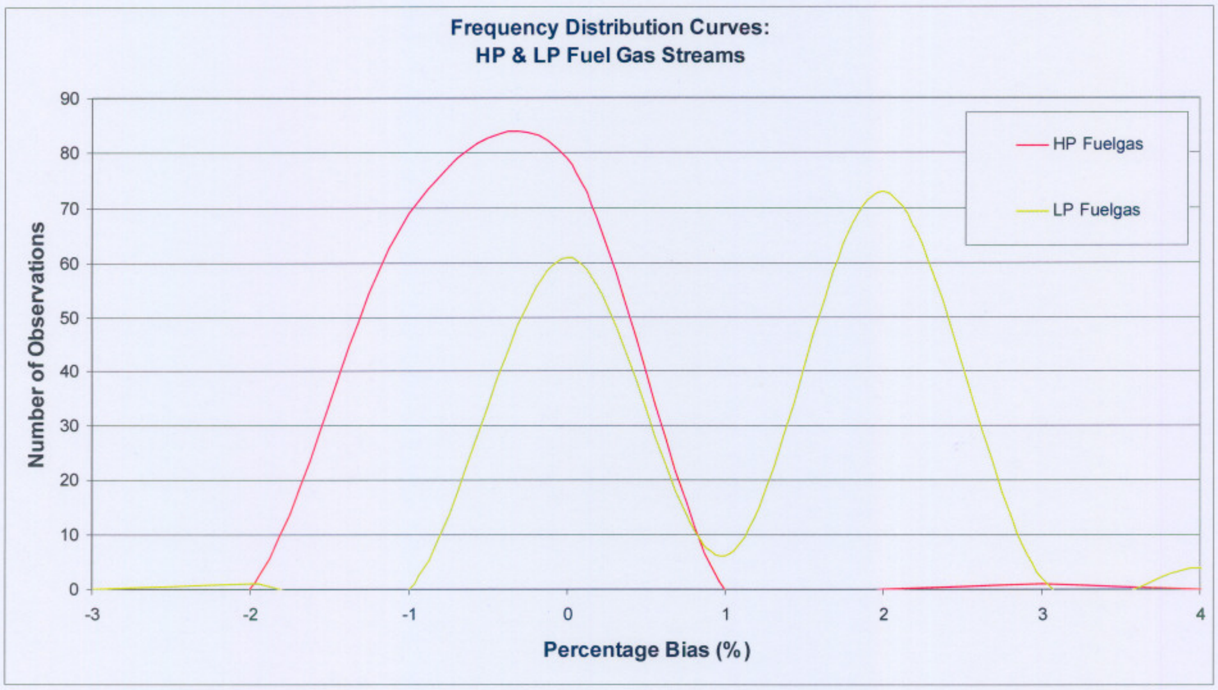


Figure 18: Frequency distribution curves of the HP & LP fuel gas streams

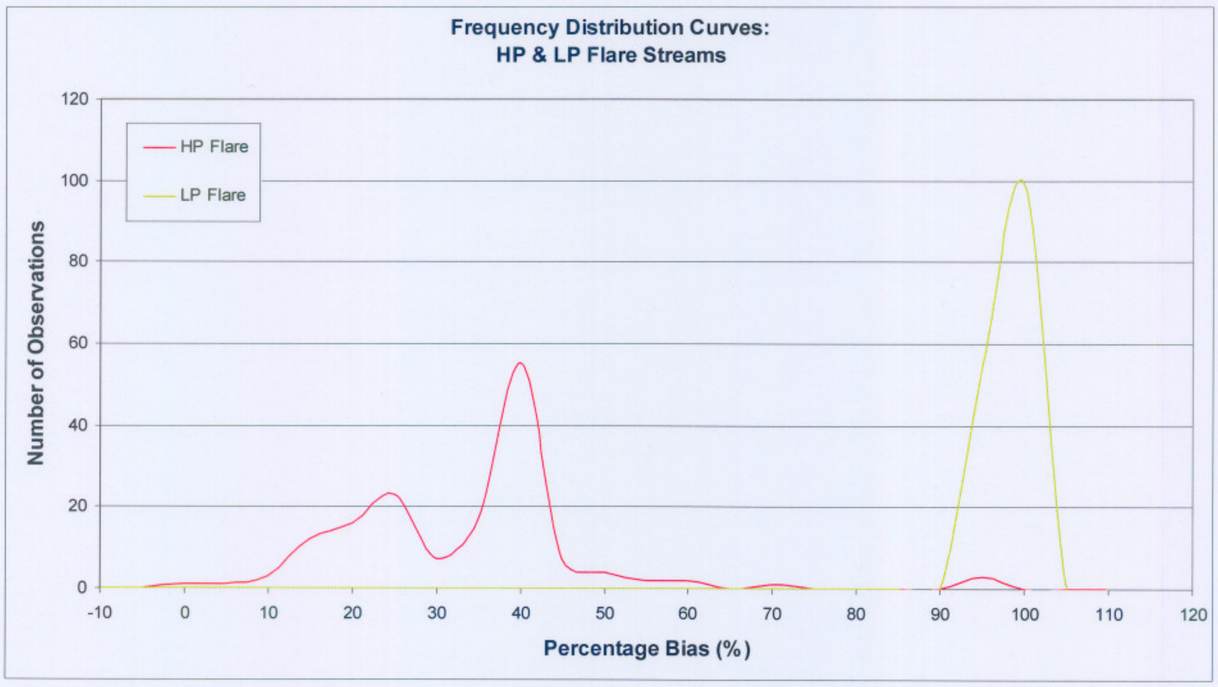


Figure 19: Frequency distribution curves of the HP & LP flare gas streams

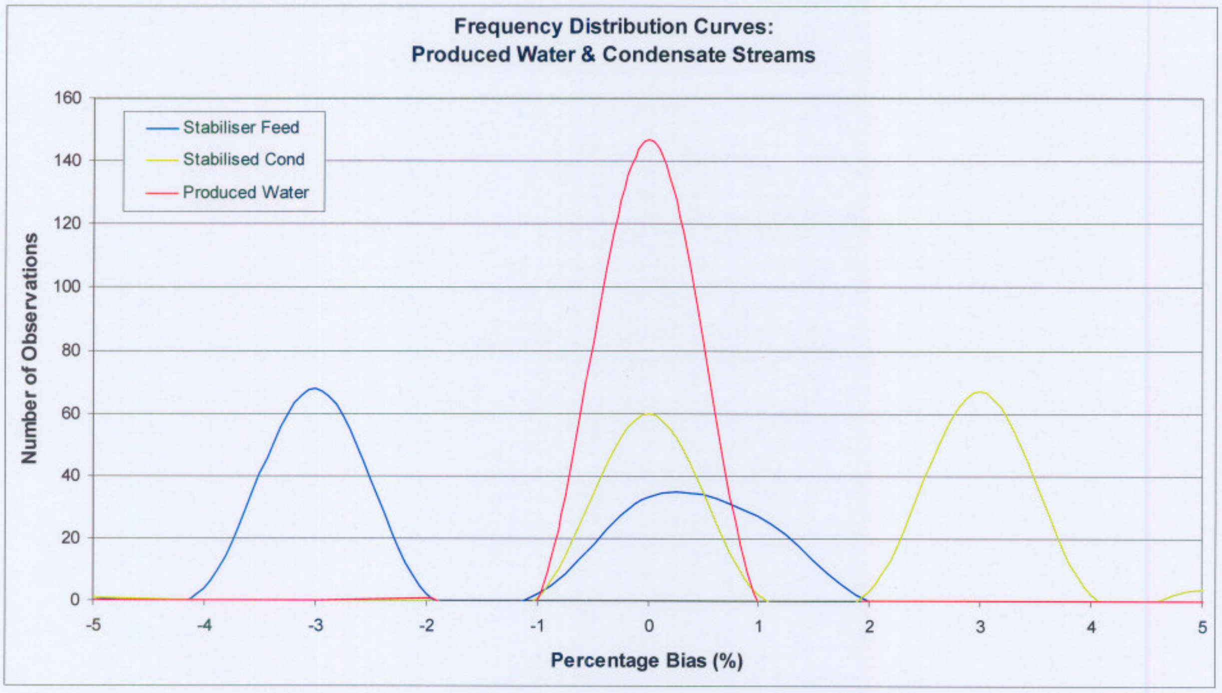


Figure 20: Frequency distribution curves of produced water & condensate streams

From Figures 14 to 20, one can clearly see two distinctive bias regimes for the Temane 14 and 15 wells, dehydration flow, LP fuel gas, HP flare, stabiliser feed, and stabilised condensate streams. Recalibration exercises were conducted on the flow meters of the above-mentioned streams throughout 2005, which would explain their shifts in bias.

4.2.2 Summary of Flow Meter Bias

Table 3 compares the biases of the flow meters after 15 October 2006. It can clearly be seen that the following flow meters have a high likelihood of miscalibration or malfunctioning: All the wells, condensation feed, condensation gas out, HP and LP fuel gas, HP and LP flares, stabiliser feed and stabilised condensate.

Stream		% Bias	Spread
No.	Description		
1	Well T3	7.4	15%
2	Well T4	7.3	14%
3	Well T5	5.9	26%
4	Well T6	1.5	31%
5	Well T7	1.4	34%
6	Well T9	0.2	47%
7	Well T10	2.0	33%
8	Well T12	4.3	21%
9	Well T13	0.7	64%
10	Well T14	4.6	33%
11	Well T15	6.0	23%
12	Well T16	0.2	32%
14	Dehydration Feed	0.0	5%
15	Condensation Feed	-24.4	19%
16	Cond Gas Out	5.5	38%
18	Export Gas	-0.6	46%
19	Concession Gas	0.0	0%
20	Incinerator Fuelgas	0.0	0%
29	HP Fuelgas	-1.1	42%
33	LP Fuelgas	1.0	62%
36	HP Flare	36.0	30%
40	LP Flare	96.0	2%
31	Stabiliser Feed	-3.9	52%
32	Stabilised Condensate	2.4	68%
30	Produced Water	-0.2	55%

Table 3: Percentage bias of all the flow meters

Experienced operators confirmed gross errors on all the well flow meters, the condensation feed, condensation gas out, HP and LP flares.

4.2.3 Correction Coefficients

In order to minimise the distortion effect that outlying preprocessing results would have on the estimated flow meter bias, the median values of six-months' results were used to calculate the respective *correction coefficients* for every flow meter with equation (2.31).

4.3 STEADY-STATE TESTING

In order to commence with steady-state testing on the process, it was first necessary to test for any auto-correlation between the data points of each measured variable and cross-correlation between the measured variables. The testing was done graphically, as shown by the following two figures. Figure 21 clearly shows no auto-correlation between data points of the Export Gas flow. Figure 22 also shows no cross-correlation between the Export Gas and the Dehydration Feed flows.

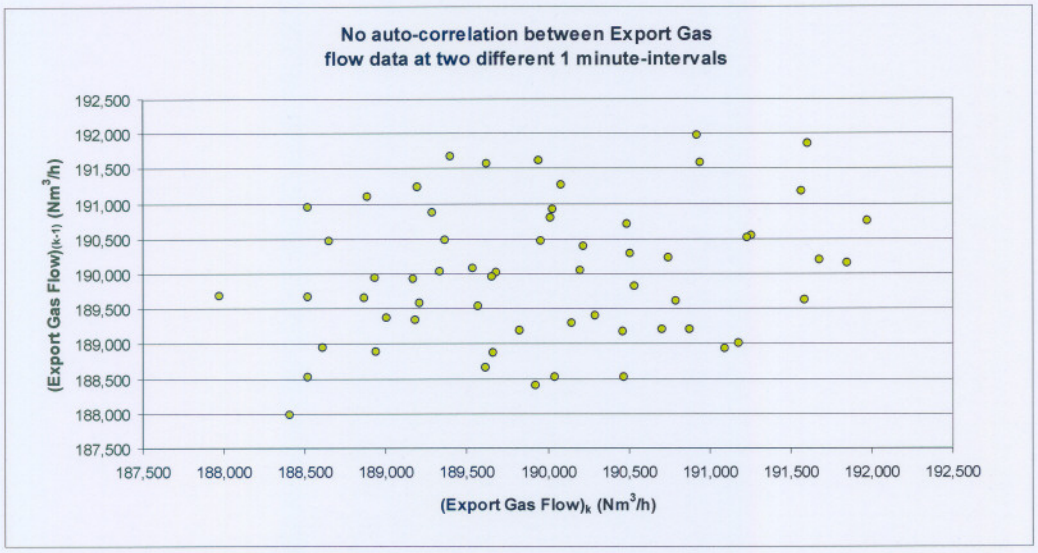


Figure 21: No auto-correlation between Export Gas flow data at two different one minute-intervals

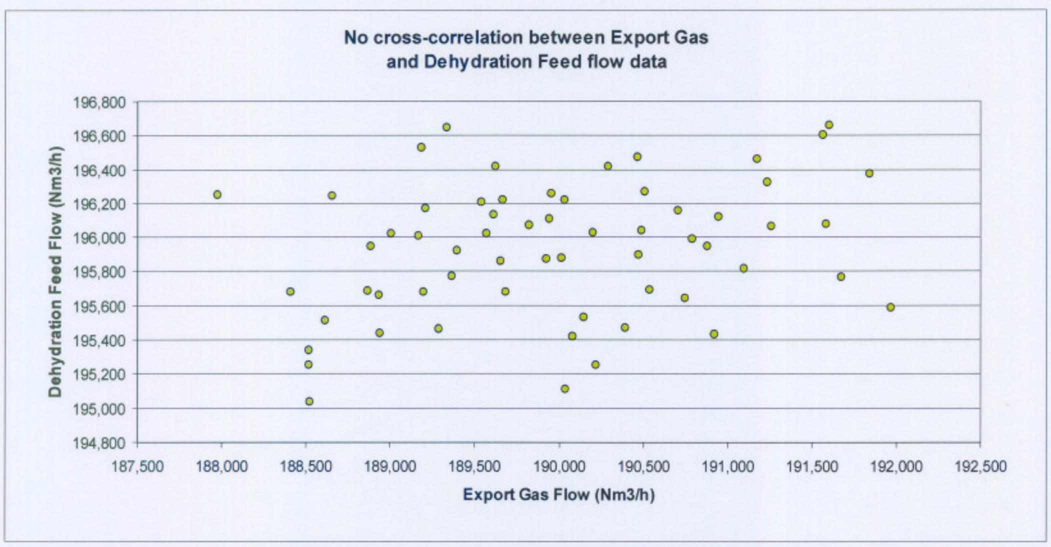


Figure 22: No cross-correlation between Export Gas and Dehydration Feed flow data

A steady-state test, using the *multivariable method*, was conducted on two hour's measured data from 00h00 to 02h00 on 16 October 2005. Twenty two variables were monitored for steady-state identification: flows of all the well streams, the dehydration feed, condensation feed, condensation gas out, export gas, concession gas, incinerator fuel gas, high pressure fuel gas, low pressure fuel gas, high pressure flare, low pressure flare, stabiliser feed, stabilised condensate, and produced water. A confidence level of 95% was used to test the null hypothesis that the process was at steady-state.

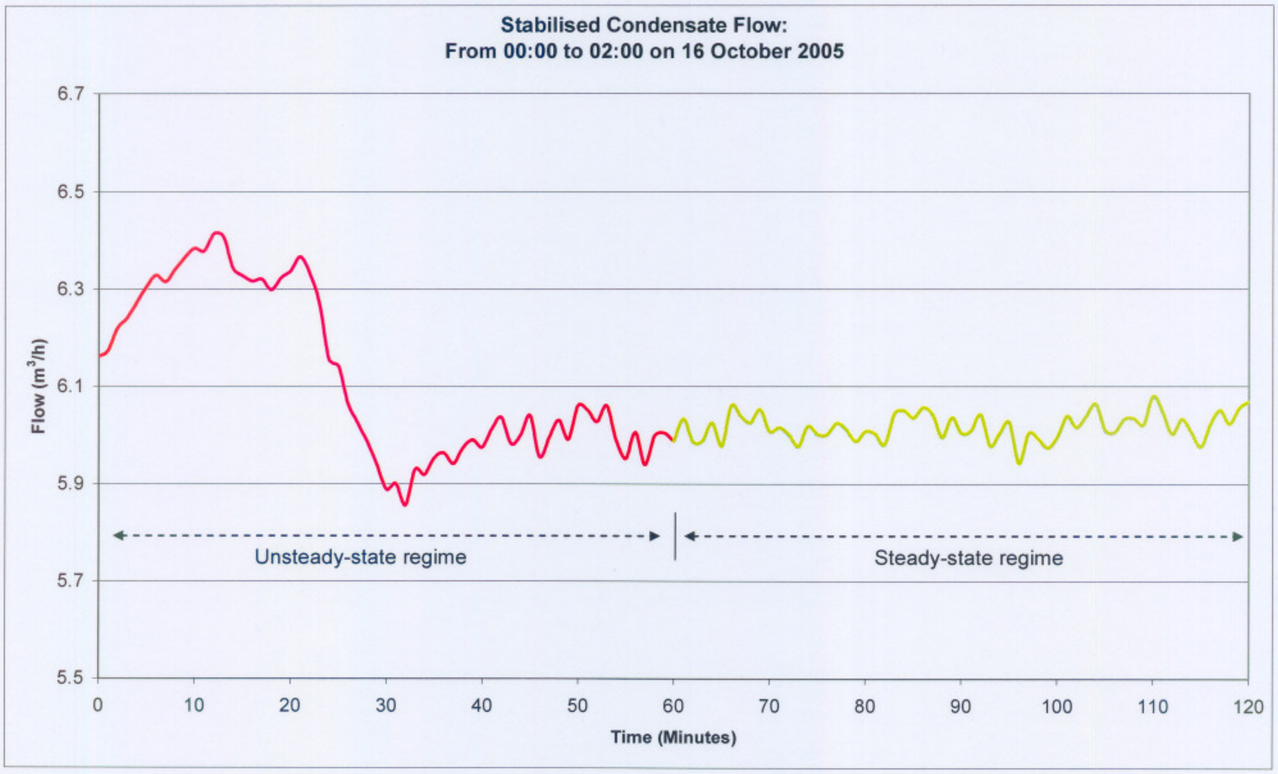


Figure 23: Stabilised condensate flow indicating steady-state change

Figure 23 shows a sample interval of two hours, indicating stabilised condensate flows during transient and steady-state periods. The first hour is marked by unsteady flow (red line), which changes to steady-state flow after 01h00 (green line). Data from the steady-state period between 01h00 and 02h00 was used further on in the reconciliation process.

4.4 GROSS ERROR HANDLING

Gross error handling was done on the measured data for the period from 01h00 to 02h00 on 16 October 2005, to minimise bias on the flow meters. This was done by multiplying each flow meter with its respective *correction coefficient*, which was derived from multiple data reconciliation exercises on historic data (see 4.2). It was assumed that all the flow meters had some degree of bias, and therefore, gross error handling was done on all of them. Table 4 gives a summary of the measured flow meter readings, their respective *correction coefficients*, and the corrected flow values, which was used further on in the reconciliation process:

Stream		Correction	Measured Flow	Corrected Flow
No.	Description	Coefficient	Nm^3/h	Nm^3/h
1	Well T3	0.93	23,848	22,074
2	Well T4	0.93	23,134	21,454
3	Well T5	0.94	25,268	23,781
4	Well T6	0.99	11,211	11,044
5	Well T7	0.99	11,245	11,086
6	Well T9	1.00	-	-
7	Well T10	0.98	16,508	16,182
8	Well T12	0.96	25,267	24,174
9	Well T13	0.99	-	-
10	Well T14	0.95	36,309	34,643
11	Well T15	0.94	28,270	26,579
12	Well T16	1.00	8,814	8,799
14	Dehydration Feed	1.00	195,930	195,938
15	Condensation Feed	1.24	154,481	192,217
16	Cond Gas Out	0.95	208,291	196,924
18	Export Gas	1.01	189,981	191,054
19	Concession Gas	1.00	395	395
20	Incinerator Fuelgas	1.00	58	58
29	HP Fuelgas	1.01	3,415	3,452
33	LP Fuelgas	0.99	446	441
36	HP Flare	0.64	394	252
40	LP Flare	0.04	475	19
31	Stabiliser Feed	1.04	1,485	1,544
32	Stabilised Condensate	0.98	978	955
30	Produced Water	1.00	353	354

Table 4: Comparison between measured and corrected flow rates

4.5 DATA RECONCILIATION

The material balance was reconciled by minimising the *weighted least-square* residual between the corrected and reconciled stream values and by satisfying all the nodal balance constraints with the help of *Microsoft Excel's* 'Solver' function. A comparison between the corrected and reconciled flow data can be seen in Table 5:

Stream		Corrected Flow	Reconciled Flow	Correction
No.	Description	Nm^3/h	Nm^3/h	%
1	Well T3	22,074	22,040	-0.15
2	Well T4	21,454	21,455	0.01
3	Well T5	23,781	23,784	0.02
4	Well T6	11,044	11,045	0.00
5	Well T7	11,086	11,086	0.00
6	Well T9	0	0	0.00
7	Well T10	16,182	16,182	0.00
8	Well T12	24,174	24,175	0.00
9	Well T13	0	0	0.00
10	Well T14	34,643	34,644	0.00
11	Well T15	26,579	26,580	0.00
12	Well T16	8,799	8,800	0.00
14	Dehydration Feed	195,938	195,944	0.00
15	Condensation Feed	192,217	194,588	1.23
16	Cond Gas Out	196,924	194,588	-1.19
18	Export Gas	191,054	194,136	1.61
19	Concession Gas	395	395	-0.06
20	Incinerator Fuelgas	58	58	0.00
29	HP Fuelgas	3,452	3,452	0.00
33	LP Fuelgas	441	441	0.00
36	HP Flare	252	235	-6.83
40	LP Flare	19	34	80.42
31	Stabiliser Feed	1,544	1,544	0.00
32	Stabilised Condensate	955	955	0.01
30	Produced Water	354	354	-0.02

Table 5: Corrected versus reconciled flow data

The *material balance calculation sheet* (Table 6) contains columns with the measured, corrected, reconciled, and calculated variables.

Values for the measured variables were obtained from their respective flow meters, which measure in Nm^3/h.

The converted variables, like the produced water, stabiliser feed and the stabilised condensate, are measured in m^3/h, and it was necessary to convert their measurement values from m^3/h to Nm^3/h. The liquid volumetric flows were multiplied with their respective densities, obtained from laboratory analyses, to obtain mass flow rate, and divided by their respective molecular weights (obtained from laboratory analyses), to obtain their respective molar flow rates. The ideal gas law was used to calculate the volumetric flow rate at normal conditions (101.325 kPa and 273.15 K).

The corrected variables were obtained by multiplying the measured and converted variables with their respective *correction coefficients*, determined from the *gross error handling* step (*see* 4.4).

The reconciled variables are the product of the data reconciliation process, where all the nodes are balanced and the sum of the residual errors between the corrected and reconciled variables are minimised.

The calculated variables are the unmeasured variables estimated from the reconciled variables.

The *mean absolute deviation* of each measured stream was used, instead of the *standard deviation*, in the calculation of the *residual error*, to minimise the effect of outliers (*see* 2.7.1).

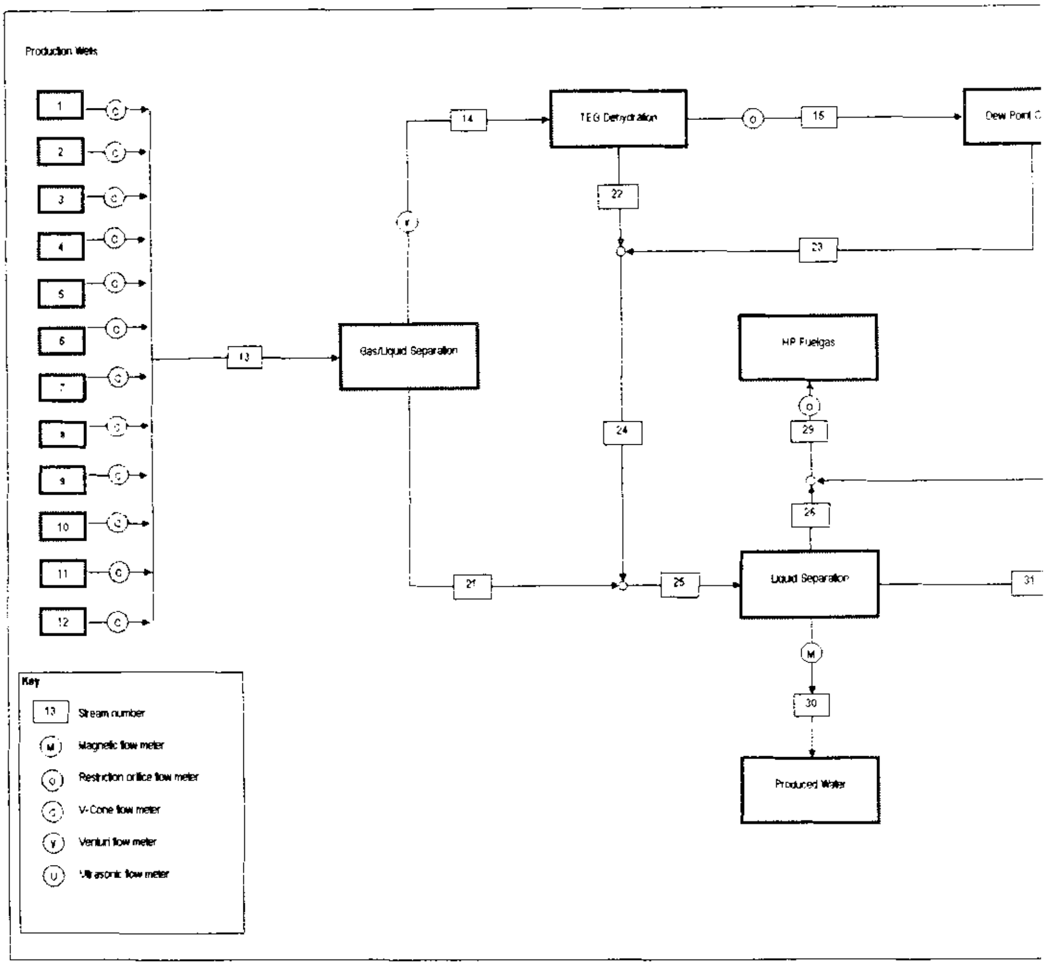
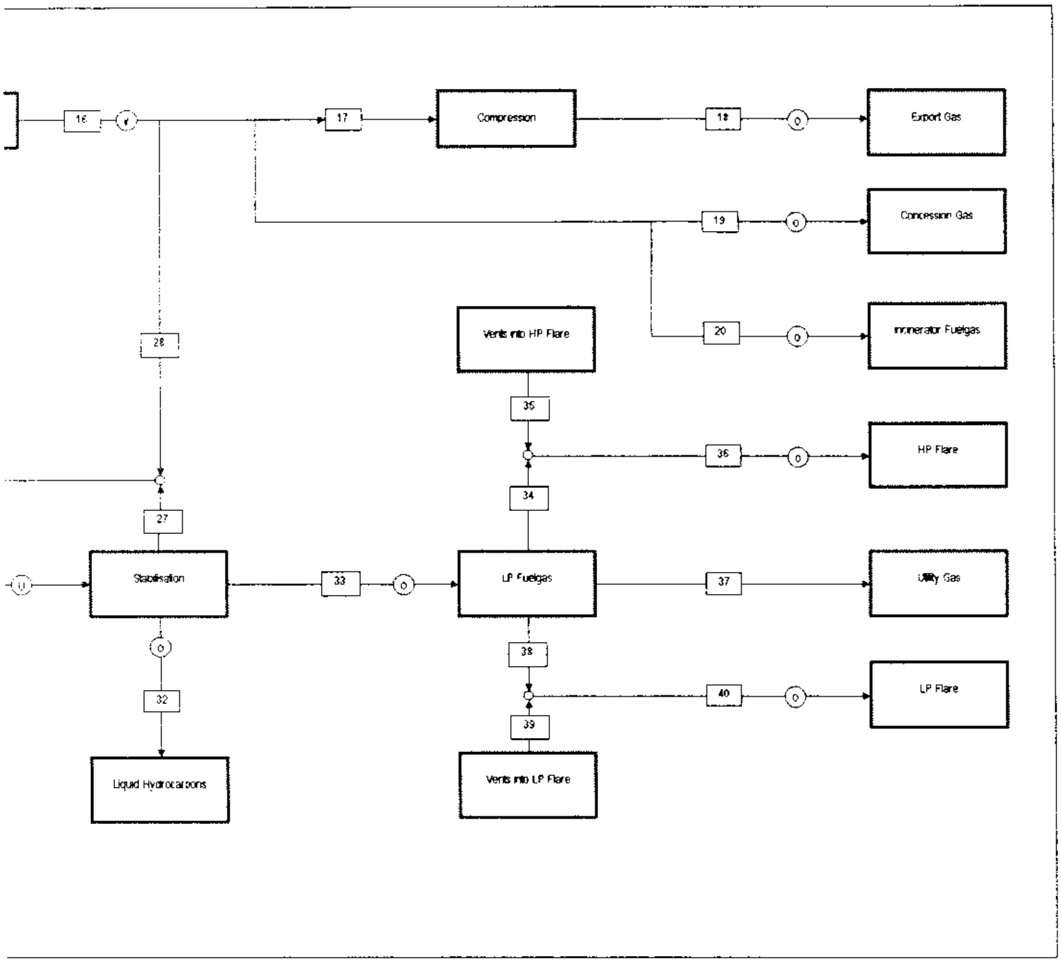


Diagram Description	Stream No	Measured Flow Nm³/h	Corrected Flow Nm³/h	Reconciled Flow Nm³/h	Calculated Flow Nm³/h	Estimation Coefficient	k	S_i	$k_i^2(M_i-M_i')^2/S_i^2$	1 Wells	2 Separation
Temane 3	1	23,848.108	22,073.897	22,040.158		0.998	1	112	0	22,040.158	
Temane 4	2	23,134.268	21,453.536	21,455.062		1.000	1	33	0	21,455.062	
Temane 5	3	25,267.675	23,780.868	23,784.458		1.000	1	14	0	23,784.458	
Temane 6	4	11,210.564	11,044.288	11,044.624		1.000	1	21	0	11,044.624	
Temane 7	5	11,245.076	11,086.068	11,086.178		1.000	1	4	0	11,086.178	
Temane 9	6	0.000	0.000	0.000		0.000	1	0	0	0.000	
Temane 10	7	16,507.847	16,181.651	16,181.847		1.000	1	11	0	16,181.847	
Temane 12	8	25,266.932	24,174.321	24,174.835		1.000	1	16	0	24,174.835	
Temane 13	9	0.000	0.000	0.000		0.000	1	0	0	0.000	
Temane 14	10	36,308.615	34,642.667	34,643.584		1.000	1	24	0	34,643.584	
Temane 15	11	28,269.524	26,579.363	26,579.941		1.000	1	19	0	26,579.941	
Temane 16	12	8,813.532	8,799.394	8,799.611		1.000	1	12	0	8,799.611	
Dehydration Feed	14	195,930.361	195,938.308	195,943.604		1.000	1	319	0		-195,943.604
Condensation Feed	15	154,481.413	192,217.384	134,588.345		1.012	1	458	27		
Condensation Gas Out	16	208,290.534	196,924.047	194,588.345		0.988	1	366	41		
Export Gas	18	189,981.302	191,054.122	194,135.839		1.016	1	802	15		
Concession Gas	19	394.907	394.906	394.676		0.999	1	0	0		
Incinerator Fuelgas	20	57.831	57.831	57.831		1.000	1	0	0		
HP Fuelgas	29	3,414.735	3,451.688	3,451.744		1.000	1	13	0		
LP Fuelgas	33	446.110	441.429	441.429		1.000	1	1	0		
HP Flare	36	393.826	252.160	234.937		0.932	1	5	13		
LP Flare	40	474.736	19.005	34.290		1.804	1	12	2		
HP Flare Purge	34	192.000	235.275	234.937		0.999	1	0	0		
LP Flare Purge	38	34.000	34.561	34.290		0.992	1	0	0		
Stabiliser Feed	31	1,485.419	1,543.614	1,543.636		1.000	1	3	0		
Stabilised Condensate	32	977.764	954.775	954.879		1.000	1	4	0		
Produced Water	30	253.365	353.969	353.901		1.000	1	1	0		
Raw Gas	13				199,790.298		0	0	0	-199,790.298	199,790.298
Compression Suction	17				194,135.839		0	0	0		
Separation Liquid	21				3,846.694		0	0	0		-3,846.694
Dehydration Liquid	22				1,355.259		0	0	0		
Condensation Liquid	23				0.000		0	0	0		
Recovered Liquids	24				1,355.259		0	0	0		
Liquid Separation Feed	25				5,201.953		0	0	0		
Liquid Separation HP Fuel Gas	26				3,304.415		0	0	0		
Stabiliser HP Fuelgas	27				147.321		0	0	0		
HP Fuelgas Makeup	28				0.000		0	0	0		
HP Vents	35				0.000		0	0	0		
Utility Gas	37				172.202		0	0	0		
LP Vents	39				0.000		0	0	0		
Residual									97	0.000	0.000

Table 6: Material balance calculation sheet



Nodal Balance												
	4	5	6	7	8	9	10	11	12	13	14	15
ation	Condensation	Distribution	Compression	Recovery	Liquid Mix	Liquid Separation	Stabilisation	HP Fuelgas Mix	LP Fuelgas Mix	HP Flare Mix	LP Flare Mix	Overall
												22,040.158
												21,455.062
												23,784.458
												11,044.624
												11,086.178
												0.000
												16,181.847
												24,174.835
												0.000
												34,643.584
												26,579.941
												8,799.611
43.604												
88.345	194,588.345											
	-194,588.345	194,588.345										
			-194,135.839									-194,135.839
		-394.676										-394.676
		-57.831										-57.831
								-3,451.744				-3,451.744
							-441.429		441.429			
										-234.937		-234.937
											-34.290	-34.290
									-234.937	234.937		
									-34.290		34.290	
						-1,543.636	1,543.636					
							-954.879					-954.879
						-353.901						-353.901
		-194,135.839	194,135.839									
					3,846.694							
55.259				1,355.259								
	0.000			0.000								
				-1,355.259	1,355.259							
					-5,201.953	5,201.953						
						-3,304.415		3,304.415				
							-147.328	147.328				
		0.000						0.000				
										0.000		
									-172.202			-172.202
											0.000	
0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000

4.6 VERIFICATION OF DATA RECONCILIATION RESULTS

A sensitivity analysis was done to establish the reliability of the data reconciliation results. Data reconciliation was conducted on data from 60 time intervals between 01h00 and 02h00 on 16 October 2005. The *percentage mean absolute deviation* was used as reference between the measured and reconciled flows, to reduce the error of outlying data. From Table 7, it can be seen that data reconciliation had a marked improvement on the sensitivity of the data, by reducing the percentage mean absolute deviation of all the streams.

Stream		Measured	Reconciled	Difference
No.	Description	% Mean Abs Dev	% Mean Abs Dev	%
1	Well T3	0.470	0.085	-81.9
2	Well T4	0.167	0.058	-65.2
3	Well T5	0.057	0.052	-9.0
4	Well T6	0.184	0.045	-75.3
5	Well T7	0.073	0.031	-57.7
6	Well T9	0.000	0.000	0.0
7	Well T10	0.067	0.030	-54.9
8	Well T12	0.063	0.043	-32.3
9	Well T13	0.000	0.000	0.0
10	Well T14	0.065	0.051	-22.1
11	Well T15	0.066	0.037	-44.8
12	Well T16	0.136	0.044	-67.4
14	Dehydration Feed	0.163	0.040	-75.4
15	Condensation Feed	0.297	0.270	-9.0
16	Cond Gas Out	0.175	0.134	-23.5
18	Export Gas	0.422	0.034	-92.0
19	Concession Gas	0.000	0.000	0.0
20	Incinerator Fuelgas	0.103	0.031	-70.1
29	HP Fuelgas	0.383	0.093	-75.8
33	LP Fuelgas	0.151	0.048	-68.6
36	HP Flare	1.208	0.017	-98.6
40	LP Flare	2.421	0.092	-96.2
31	Stabiliser Feed	0.218	0.025	-88.6
32	Stabilised Condensate	0.379	0.059	-84.5
30	Produced Water	0.422	0.071	-83.2

Table 7: Percentage mean absolute deviations of the measured versus the reconciled variables

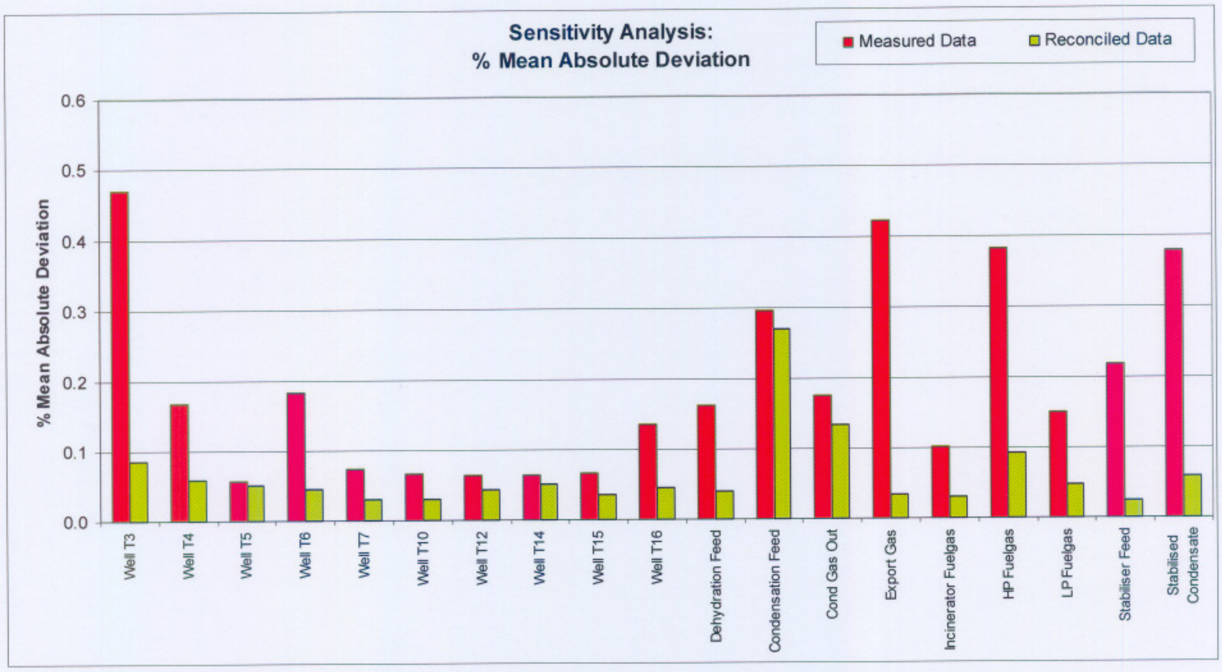


Figure 24: Percentage mean absolute deviation comparison between measured and reconciled data

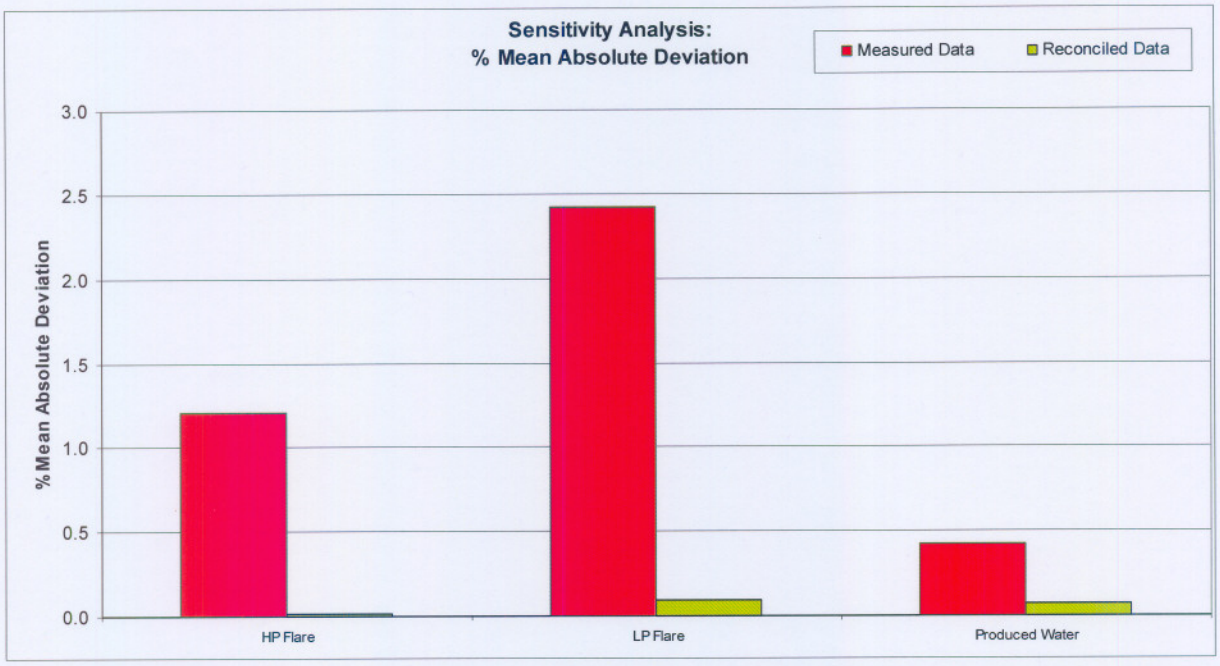
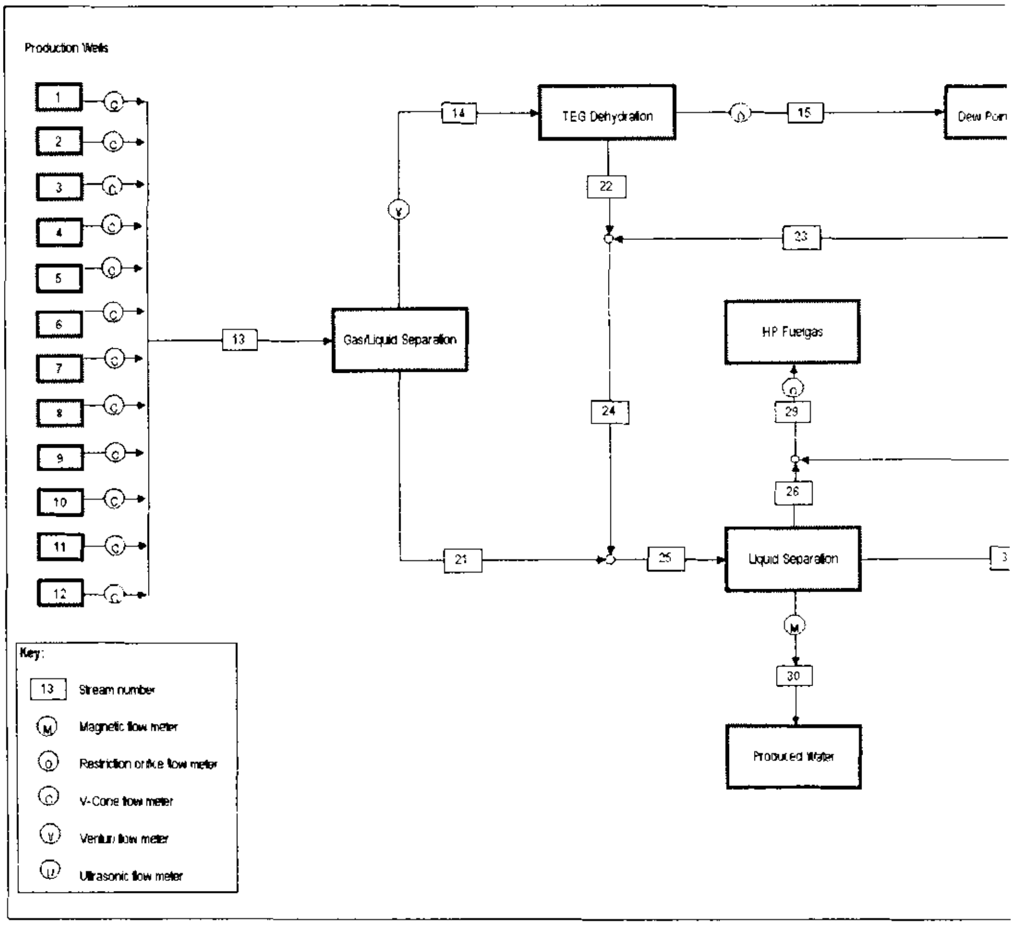


Figure 25: Percentage mean absolute deviation comparison between measured and reconciled data

Figures 24 and 25 give a comparison of the percentage mean absolute deviations between the measured and reconciled data. Data reconciliation increased the sensitivity of all the streams' data, with marked reductions in the percentage mean absolute deviations of all the streams after reconciliation compared to the measured values.

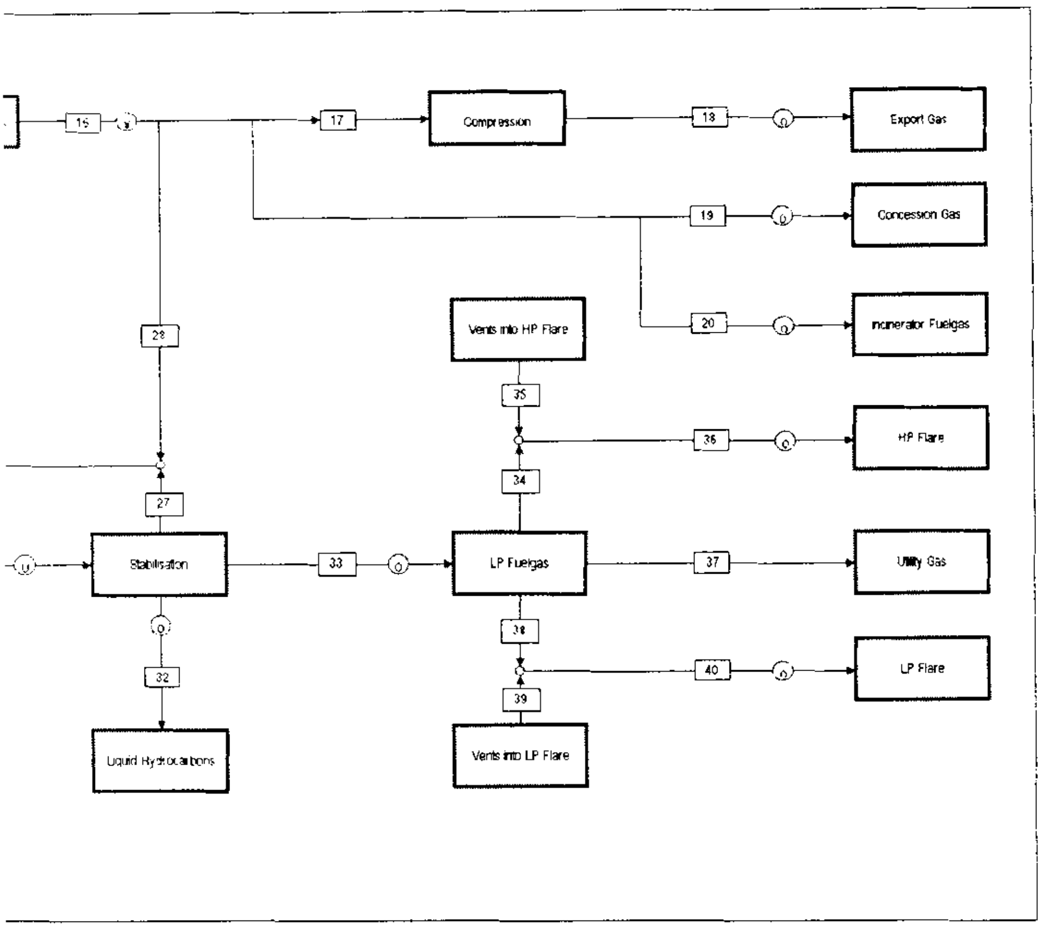
4.7 MATERIAL BALANCE

The reconciled material balance of the plant between 01h00 and 02h00 on 16 October 2005 appears in Table 8. The 'Solver' function in *Microsoft Excel* was used to adjust the initial property and composition values, obtained from laboratory analyses for the individual measured streams, to satisfy the constraints set by the volumetric, energy, mass and component balances.



Material Balance Diagram Description	Stream No.	Reconciled Volume Flow Nm^3/h	Reconciled Energy Flow GJ/h	Reconciled Mass Flow kg/h	Reconciled Heating Value MJ/Nm^3	Reconciled Normal Density kg/Nm^3	Reconciled C_1 Vol %	Reconciled C_2 Vol. %	Reconciled C_3 Vol %	Reconciled C_4 Vol %
Temane 3	1	22,040.2	1,044.6	20,075.5	47.40	0.91	87.67	3.01	1.63	1.31
Temane 4	2	21,455.1	915.8	17,408.1	42.69	0.81	90.24	3.14	1.95	0.98
Temane 5	3	23,784.5	1,020.4	19,236.7	42.90	0.81	91.75	2.58	1.28	0.75
Temane 6	4	11,044.6	495.7	9,460.8	44.88	0.86	89.05	3.22	2.05	1.22
Temane 7	5	11,086.2	447.0	8,336.2	40.32	0.75	94.92	0.92	1.65	0.02
Temane 9	6	0.0	0.0	0.0	0.00	0.00	0.00	0.00	0.00	0.00
Temane 10	7	16,181.8	718.8	13,505.9	44.42	0.83	91.38	2.61	1.35	0.85
Temane 12	8	24,174.8	1,048.5	19,927.2	43.37	0.82	89.90	3.18	1.76	1.14
Temane 13	9	0.0	0.0	0.0	0.00	0.00	0.00	0.00	0.00	0.00
Temane 14	10	34,643.6	1,560.8	29,765.1	45.05	0.86	83.14	3.69	2.04	1.43
Temane 15	11	26,579.9	1,201.5	23,008.6	45.20	0.87	88.94	3.01	1.62	1.09
Temane 16	12	8,799.6	382.8	7,196.6	43.60	0.82	91.78	2.42	1.34	0.82
Dehydration Feed	14	195,943.6	8,719.4	164,186.1	44.50	0.84	90.83	2.99	1.69	1.03
Condensation Feed	15	194,588.3	8,338.0	158,156.8	42.85	0.81	91.08	2.99	1.63	0.97
Condensation Gas Out	16	194,588.3	8,338.0	158,156.8	42.85	0.81	91.08	2.99	1.63	0.97
Export Gas	18	194,135.8	8,318.6	157,789.0	42.85	0.81	91.08	2.99	1.63	0.97
Concession Gas	19	394.7	16.9	320.8	42.85	0.81	91.08	2.99	1.63	0.97
Incinerator Fuelgas	20	57.8	2.5	47.0	42.85	0.81	91.08	2.99	1.63	0.97
HP Fuelgas	29	3,451.7	183.2	3,643.2	53.07	1.06	80.93	1.91	4.23	3.27
LP Fuelgas	33	441.4	38.0	905.8	86.04	2.05	9.65	3.17	16.02	20.62
HP Flare	36	234.9	20.2	482.1	86.04	2.05	9.65	3.17	16.02	20.62
LP Flare	40	34.3	3.0	70.4	86.05	2.05	9.65	3.17	16.02	20.62
HP Flare Purge	34	234.9	20.2	482.1	86.04	2.05	9.65	3.17	16.02	20.62
LP Flare Purge	38	34.3	3.0	70.4	86.04	2.05	9.65	3.17	16.02	20.62
Stabiliser Feed	31	1,543.6	323.8	5,472.2	209.79	3.54	8.31	1.12	4.76	6.04
Stabilised Condensate	32	954.9	266.7	4,136.2	279.28	4.33	0.34	0.01	0.00	0.00
Produced Water	30	353.9	10.1	1,078.8	28.58	3.05	0.00	0.26	1.58	1.46
Raw Gas	13	199,790.3	8,835.9	167,320.7	44.23	0.84	90.13	2.95	1.70	1.05
Compression Suction	17	194,135.8	8,318.6	157,789.0	42.85	0.81	91.08	2.99	1.63	0.97
Separation Liquid	21	3,846.7	116.6	3,734.6	30.30	0.97	64.45	1.16	2.27	2.01
Dehydration Liquid	22	1,355.3	381.4	6,029.3	281.42	4.45	54.94	2.67	9.95	9.72
Condensation Liquid	23	0.0	0.0	0.0	0.00	0.00	0.00	0.00	0.00	0.00
Recovered Liquids	24	1,356.3	381.4	6,029.3	281.42	4.45	54.94	2.67	9.95	9.72
Liquid Separation Feed	25	5,202.0	498.0	9,764.0	95.73	1.88	54.59	1.56	4.27	4.02
Liquid Separation HP Fuelgas	26	3,304.4	164.0	3,213.0	49.63	0.97	82.04	1.90	4.33	3.35
Stabiliser HP Fuelgas	27	147.3	19.2	430.2	130.21	2.92	55.95	2.16	1.86	1.43
HP Fuelgas Makeup	28	0.0	0.0	0.0	0.00	0.00	0.00	0.00	0.00	0.00
HP Vents	35	0.0	0.0	0.0	0.00	0.00	0.00	0.00	0.00	0.00
Utility Gas	37	172.2	14.8	353.4	86.04	2.05	9.65	3.17	16.02	20.62
LP Vents	39	0.0	0.0	0.0	0.00	0.00	0.00	0.00	0.00	0.00
Residual		0.0	0.0	0.0						

Table 8: Reconciliated material balance



d	Reconciled N_2 Vol %	Reconciled H_2O Vol. %	Calculated Total Vol %	Reconciled C_1 Nm^3/h	Reconciled C_2 Nm^3/h	Reconciled C_3 Nm^3/h	Reconciled C_4 Nm^3/h	Reconciled C_{5+} Nm^3/h	Reconciled N_2 Nm^3/h	Reconciled H_2O Nm^3/h	Calculated Total Nm^3/h	Calculated Residual Nm^3/h
.52	2.48	0.38	100.0	19,321.6	663.9	359.3	289.6	775.3	546.6	83.9	22,040.2	0.0
.64	2.55	0.39	100.0	19,360.7	674.3	418.9	210.3	137.3	568.9	84.0	21,455.1	0.0
12	2.15	0.37	100.0	21,822.7	612.6	304.5	177.9	266.5	511.6	88.7	23,784.5	0.0
.29	2.42	0.65	100.0	9,835.3	355.7	226.2	145.7	153.1	267.0	60.6	11,044.6	0.0
.02	1.93	0.56	100.0	10,523.0	102.3	182.4	2.1	0.2	214.6	61.7	11,086.2	0.0
.00	0.00	0.00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
.18	1.58	0.44	100.0	14,883.4	423.0	218.4	137.8	191.6	256.0	71.5	16,181.8	0.0
.08	2.56	0.37	100.0	21,732.3	769.9	425.0	275.5	261.8	620.1	90.3	24,174.8	0.0
.00	0.00	0.00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
.05	2.34	0.30	100.0	30,880.6	1,279.9	708.0	496.3	353.2	812.0	103.4	34,643.6	0.0
.38	2.63	0.35	100.0	23,639.2	799.7	430.5	287.5	632.0	697.8	93.1	26,579.9	0.0
.33	1.68	0.64	100.0	8,076.3	213.2	117.7	72.1	116.7	147.8	56.0	8,799.6	0.0
[illegible]	2.34	0.27	100.0	177,980.3	5,849.9	3,303.4	2,019.2	1,671.0	4,683.4	536.2	195,943.6	0.0
[illegible]	2.32	0.21	100.0	177,235.8	5,813.7	3,168.6	1,887.5	1,561.4	4,521.5	399.8	194,588.3	0.0
[illegible]	2.32	0.21	100.0	177,235.8	5,813.7	3,168.6	1,887.5	1,561.4	4,521.5	399.8	194,588.3	0.0
[illegible]	2.32	0.21	100.0	176,823.6	5,800.2	3,161.2	1,883.1	1,557.8	4,511.0	398.9	194,135.8	0.0
[illegible]	2.32	0.21	100.0	359.5	11.8	6.4	3.8	3.2	9.2	0.8	394.7	0.0
.80	2.32	0.21	100.0	52.7	1.7	0.9	0.6	0.5	1.3	0.1	57.8	0.0
5.92	1.75	2.01	100.0	2,793.3	65.9	145.9	112.7	204.3	60.3	69.2	3,451.7	0.0
2.70	2.52	5.32	100.0	42.6	14.0	70.7	91.0	138.5	11.1	23.5	441.4	0.0
2.70	2.52	5.32	100.0	22.7	7.5	37.6	48.5	100.3	5.9	12.5	234.9	0.0
2.70	2.52	5.32	100.0	3.3	1.1	5.5	7.1	14.6	0.9	1.8	34.3	0.0
2.70	2.52	5.32	100.0	22.7	7.5	37.6	48.5	100.3	5.9	12.5	234.9	0.0
2.70	2.52	5.32	100.0	3.3	1.1	5.5	7.1	14.6	0.9	1.8	34.3	0.0
3.02	1.37	5.38	100.0	128.3	17.3	73.5	93.2	1,127.2	21.2	83.1	1,543.6	0.0
4.25	0.99	0.41	100.0	3.2	0.1	0.0	0.0	938.2	9.5	3.3	954.9	0.0
1.51	11.31	83.87	100.0	0.0	0.9	5.6	5.2	5.4	40.0	296.8	353.9	0.0
1.45	2.32	0.40	100.0	180,075.0	5,894.6	3,390.9	2,096.5	2,897.7	4,642.4	793.2	199,790.3	0.0
0.80	2.32	0.21	100.0	176,823.6	5,800.2	3,161.2	1,883.1	1,557.8	4,511.0	398.9	194,135.8	0.0
.89	1.53	6.68	100.0	2,094.7	44.6	87.4	77.3	1,226.7	59.0	257.0	3,846.7	0.0
8.09	4.57	10.07	100.0	744.5	36.2	134.8	131.7	109.6	61.9	136.4	1,365.3	0.0
[illegible]	0.00	0.00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
8.09	4.57	10.07	100.0	744.5	36.2	134.8	131.7	109.6	61.9	136.4	1,355.3	0.0
[illegible]	2.32	7.56	100.0	2,839.2	80.9	222.3	209.0	1,336.3	120.9	393.4	5,202.0	0.0
6.17	1.21	0.41	100.0	2,710.9	62.7	143.2	110.6	203.8	59.7	13.6	3,304.4	0.0
[illegible]	0.44	37.79	100.0	82.5	3.2	2.7	2.1	0.5	0.6	55.7	147.3	0.0
0.00	0.00	0.00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.00	0.00	0.00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2.70	2.52	5.32	100.0	15.6	5.5	27.6	35.5	73.5	4.3	9.2	172.2	0.0
0.00	0.00	0.00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
				0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

CHAPTER 5

CONCLUSIONS & RECOMMENDATIONS

5.1 CONCLUSIONS

5.1.1 A literature study was done and mathematical techniques for the reconciliation of plant data, and statistical methods to verify the results, were obtained.

5.1.2 Spreadsheets were created in *Microsoft Excel*, to: process raw input data; derive correction coefficients from historic data; conduct steady-state testing; eliminate gross errors; reconcile the material balance, and verify the results via a sensitivity analysis.

5.1.3 It was concluded that the material balance of a natural gas processing plant could be reconciled successfully, with the help of *Microsoft Excel.*

5.2 RECOMMENDATIONS

5.2.1 Use the procedure set out in this dissertation to reconcile the material balance of a natural gas processing plant with the help of *Microsoft Excel.*

5.2.2 The following flow meters should be recalibrated and checked for malfunctioning: all the well flow meters, condensation feed, condensation gas out, export gas, high and low pressure fuel gas, high and low pressure flares, stabiliser feed and stabilised condensate flow meters.

5.2.3 Add new flow meters on the high and low pressure vents, to obtain more accurate material balances of the plant. This measure will reveal process leaks and identify optimisation opportunities, especially related to reducing flare emissions and improving the overall efficiency of the plant.

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APPENDIX A: RAW DATA

Appendix A contains raw DCS data from 01:00 to 02:00 on 16 October 2005, which was used in the data reconciliation process.

Raw Data	Well T3	Well T4	Well T5	Well T6	Well T7	Well T9	Well T10
	Stream 1	Stream 2	Stream 3	Stream 4	Stream 5	Stream 6	Stream 7
	Nm^3/h	Nm^3/h	Nm^3/h	Nm^3/h	Nm^3/h	Nm^3/h	Nm^3/h
2005/10/16 01:00:00	23,848.506	23,054.287	25,266.299	11,179.370	11,225.102	0.000	16,513.066
2005/10/16 01:01:00	23,901.512	23,107.931	25,259.782	11,181.546	11,244.534	0.000	16,479.697
2005/10/16 01:02:00	23,982.692	23,082.887	25,259.649	11,187.912	11,239.834	0.000	16,498.830
2005/10/16 01:03:00	23,998.988	23,061.569	25,281.939	11,170.081	11,251.554	0.000	16,482.194
2005/10/16 01:04:00	23,717.545	23,082.780	25,266.690	11,209.721	11,252.263	0.000	16,505.116
2005/10/16 01:05:00	23,655.040	23,092.942	25,243.290	11,180.373	11,259.939	0.000	16,513.482
2005/10/16 01:06:00	23,807.571	23,085.698	25,265.629	11,189.032	11,248.096	0.000	16,502.375
2005/10/16 01:07:00	23,896.023	23,096.177	25,258.402	11,193.698	11,243.882	0.000	16,508.496
2005/10/16 01:08:00	24,003.830	23,075.491	25,279.137	11,178.403	11,266.809	0.000	16,521.925
2005/10/16 01:09:00	23,971.593	23,063.207	25,214.787	11,198.974	11,252.334	0.000	16,503.186
2005/10/16 01:10:00	23,712.893	23,151.081	25,254.437	11,235.224	11,252.325	0.000	16,485.442
2005/10/16 01:11:00	23,644.656	23,149.942	25,222.166	11,224.278	11,251.493	0.000	16,509.217
2005/10/16 01:12:00	23,756.425	23,080.524	25,258.161	11,207.275	11,248.098	0.000	16,513.480
2005/10/16 01:13:00	23,926.640	23,095.243	25,283.088	11,191.115	11,259.991	0.000	16,521.981
2005/10/16 01:14:00	23,966.607	23,146.025	25,258.168	11,231.173	11,239.579	0.000	16,512.604
2005/10/16 01:15:00	23,955.402	23,194.717	25,295.522	11,170.732	11,237.937	0.000	16,514.373
2005/10/16 01:16:00	23,898.162	23,104.626	25,269.217	11,235.288	11,236.128	0.000	16,491.478
2005/10/16 01:17:00	23,623.611	23,153.799	25,289.523	11,263.768	11,259.053	0.000	16,511.421
2005/10/16 01:18:00	23,709.120	23,100.724	25,291.141	11,229.857	11,248.105	0.000	16,521.140
2005/10/16 01:19:00	23,878.206	23,127.694	25,269.240	11,221.670	11,246.100	0.000	16,528.774
2005/10/16 01:20:00	23,940.698	23,062.794	25,281.417	11,238.778	11,239.170	0.000	16,521.159
2005/10/16 01:21:00	23,987.266	23,079.122	25,281.507	11,189.028	11,258.890	0.000	16,504.057
2005/10/16 01:22:00	23,917.170	23,141.458	25,261.185	11,219.347	11,255.779	0.000	16,515.086
2005/10/16 01:23:00	23,641.312	23,146.067	25,276.758	11,190.367	11,246.608	0.000	16,508.977
2005/10/16 01:24:00	23,773.730	23,092.080	25,256.957	11,174.912	11,226.570	0.000	16,510.198
2005/10/16 01:25:00	23,894.566	23,117.764	25,256.289	11,219.004	11,245.060	0.000	16,522.887
2005/10/16 01:26:00	23,957.472	23,074.205	25,263.094	11,187.604	11,243.352	0.000	16,485.961
2005/10/16 01:27:00	23,975.735	23,126.952	25,300.110	11,201.758	11,249.903	0.000	16,515.114
2005/10/16 01:28:00	23,918.987	23,164.718	25,292.156	11,213.228	11,250.918	0.000	16,509.648
2005/10/16 01:29:00	23,635.808	23,129.876	25,236.809	11,243.573	11,240.578	0.000	16,523.961
2005/10/16 01:30:00	23,745.003	23,109.528	25,273.475	11,225.924	11,248.022	0.000	16,520.455
2005/10/16 01:31:00	23,849.375	23,122.758	25,295.103	11,225.192	11,261.116	0.000	16,503.090
2005/10/16 01:32:00	23,963.390	23,158.261	25,287.396	11,187.833	11,260.372	0.000	16,523.570
2005/10/16 01:33:00	23,971.505	23,191.807	25,269.595	11,213.265	11,240.815	0.000	16,486.041
2005/10/16 01:34:00	23,913.978	23,136.553	25,262.437	11,211.145	11,258.078	0.000	16,520.400
2005/10/16 01:35:00	23,612.722	23,139.909	25,254.535	11,183.238	11,243.147	0.000	16,498.315
2005/10/16 01:36:00	23,676.311	23,166.304	25,261.580	11,240.513	11,250.626	0.000	16,490.675
2005/10/16 01:37:00	23,864.573	23,176.999	25,295.654	11,228.801	11,248.208	0.000	16,483.248
2005/10/16 01:38:00	23,959.652	23,141.656	25,280.265	11,210.589	11,238.104	0.000	16,492.518
2005/10/16 01:39:00	23,964.260	23,112.850	25,277.100	11,214.980	11,242.673	0.000	16,508.390
2005/10/16 01:40:00	23,967.077	23,198.000	25,258.452	11,246.752	11,243.308	0.000	16,497.841
2005/10/16 01:41:00	23,733.662	23,190.366	25,280.642	11,166.315	11,245.014	0.000	16,518.625
2005/10/16 01:42:00	23,663.309	23,120.091	25,258.143	11,213.775	11,251.100	0.000	16,481.210
2005/10/16 01:43:00	23,814.655	23,041.032	25,261.394	11,251.743	11,232.976	0.000	16,502.186
2005/10/16 01:44:00	23,894.325	23,178.873	25,302.973	11,236.967	11,227.560	0.000	16,508.254
2005/10/16 01:45:00	23,965.885	23,138.520	25,241.267	11,209.093	11,244.623	0.000	16,528.371
2005/10/16 01:46:00	23,993.578	23,188.407	25,267.859	11,250.360	11,258.823	0.000	16,526.626
2005/10/16 01:47:00	23,723.307	23,222.070	25,273.731	11,237.654	11,240.662	0.000	16,516.860
2005/10/16 01:48:00	23,615.604	23,194.350	25,254.844	11,214.863	11,249.962	0.000	16,517.504
2005/10/16 01:49:00	23,730.803	23,103.724	25,243.654	11,225.370	11,246.261	0.000	16,513.998
2005/10/16 01:50:00	23,902.405	23,221.994	25,254.088	11,249.449	11,238.395	0.000	16,526.246
2005/10/16 01:51:00	23,933.021	23,128.880	25,271.109	11,209.065	11,230.787	0.000	16,505.009
2005/10/16 01:52:00	23,981.404	23,201.897	25,271.540	11,229.828	11,217.768	0.000	16,513.265
2005/10/16 01:53:00	23,959.243	23,156.105	25,238.610	11,212.721	11,236.024	0.000	16,520.279
2005/10/16 01:54:00	23,601.235	23,237.998	25,286.598	11,179.402	11,229.854	0.000	16,527.335
2005/10/16 01:55:00	23,709.262	23,173.637	25,271.877	11,211.691	11,254.886	0.000	16,485.411
2005/10/16 01:56:00	23,872.231	23,116.170	25,265.173	11,182.969	11,220.004	0.000	16,497.852
2005/10/16 01:57:00	23,918.803	23,140.563	25,255.004	11,157.079	11,248.805	0.000	16,510.206
2005/10/16 01:58:00	23,980.041	23,152.854	25,280.093	11,199.389	11,252.142	0.000	16,494.542
2005/10/16 01:59:00	23,977.352	23,180.954	25,249.102	11,242.670	11,227.672	0.000	16,504.693
2005/10/16 02:00:00	23,778.879	23,204.841	25,292.310	11,218.703	11,241.864	0.000	16,500.351
Average	23,848.108	23,134.268	25,267.675	11,210.564	11,245.076	0.000	16,507.847
Median	23,896.023	23,136.553	25,266.690	11,212.721	11,246.100	0.000	16,509.648
Standard Deviation	127.711	46.928	18.280	25.041	10.533	0.000	13.423
Mean Absolute Deviation	112.263	38.637	14.355	20.621	8.174	0.000	10.979
% Mean Abs Deviation	0.470	0.167	0.057	0.184	0.073	0.000	0.067

Table 9: Raw data

Well T12	Well T13	Well T14	Well T15	Well T16	Dehyd Feed	Cond Feed	Cond Gas Out	Export Gas
Stream 8	Stream 9	Stream 10	Stream 11	Stream 12	Stream 14	Stream 15	Stream 16	Stream 18
Nm^3/h	Nm^3/h	Nm^3/h	Nm^3/h	Nm^3/h	Nm^3/h	Nm^3/h	Nm^3/h	Nm^3/h
25.235.332	0.000	36.282.288	28.282.769	8.790.199	195.470.000	154.692.049	207,946.684	190.392.342
25.266.498	0.000	36,300.411	28.301.157	8.805 554	195.253.000	153,530.114	207.419.570	190,220.575
25.290.681	0.000	36,286.246	28.316.843	8.789 568	195,643.000	154,064.895	208,029.345	190,748.062
25.269.413	0.000	36,341 910	28.297.457	8.839.607	195.589.000	154.825.030	207.938.826	191.971.656
25.241.542	0.000	36.317.096	28.270.010	8.813.203	195 434.000	153,991.306	207,906.314	190.921.633
25.241.624	0.000	36.328 541	28.240.561	8.820.795	196,217.000	154,778.825	208.515.141	190.031.630
25.275 489	0.000	36,309.766	28.261.838	8,810.461	196.643.000	155,386 567	208.848.960	189,332.554
25.220 801	0.000	36,362.680	28,265.851	8,800.540	196,530.000	155.295.044	208,737.606	189,182.414
25.255.405	0.000	36.319.500	28.278.127	8.847.185	196.068.000	154.330.400	208,244.186	189.823.414
25.234.581	0.000	36.326 119	28,283.140	8.830 084	195.689 000	155,007.833	207,866.810	190,538.144
25.291.805	0.000	36,330 999	28.289.297	8.805.547	196,066.000	154,444.563	208,134.345	191,260 674
25,259 286	0 000	36.337.380	28,285 551	8,797.038	195,419.000	153.770.912	207,430.069	190,081.511
25.256.094	0 000	36.328.557	28,299.231	8.832.684	196,208.000	154,291 257	208,204.727	189.537.123
25.297 800	0.000	36.351.263	28,276.917	8,815.736	196.019 000	154,580 581	208,170.637	189.571 823
25.264.116	0 000	36,367.741	28,316.587	8,829.361	196.170.000	153.632.784	208,577.679	189,208.785
25.276.517	0.000	36,326.162	28.317.929	8,825 087	196,156.000	154.310.910	208,546.919	190,709.051
25.257.114	0.000	36.314.302	28,274.583	8.808.888	196.036.000	155.244.908	208,318.655	190,487.420
25,260.788	0.000	36.330 015	28,265.397	8.820.810	195,770.000	155,679.891	208,387.773	189,366 185
25,258.751	0.000	36,250.367	28.279.747	8.828.485	196.017.000	155.306.230	208,628.053	189,004.081
25.295 639	0.000	36.316.970	28,266.972	8,822.093	196.462.000	155.092.709	209.044.545	191.178.831
25.271.664	0.000	36.301.987	28.246.496	8.805.563	196,601.000	155.099 666	209,133.799	191.565.579
25.279 457	0.000	36.333.081	28.276.123	8.816.338	196.416.000	154,625.306	208.872.569	189.624.783
25.266.727	0.000	36.296.175	28.309.595	8.808.675	196,078 000	154.877.809	208,300.024	191,586.057
25.295.931	0.000	36,282.776	28.258.255	8,831.468	196,119.000	154.728.571	208,555.908	190,945.160
25.274.956	0.000	36,308.099	28.253.307	8,833.141	195 338.000	154.265.470	207,954.321	188.519.686
25.292.113	0.000	36.330.910	28.295.955	8.830.218	195,895.000	154,832.291	208,384.746	190 470 443
25,281.844	0.000	36,318 985	28 300.472	8.802.745	196,242.000	154,148.661	208,651.824	188.652 972
25,253.767	0.000	36,325.897	28.280.983	8,796.058	196,133.000	153.718,022	208,549 410	189,614.262
25.273.643	0.000	36.369.615	28,272.529	8.831.180	195.989.000	154.078.540	208.414.043	190.791.049
25.242.905	0.000	36.320.469	28.270.060	8.810.576	195.877.000	153.967.124	207,838.765	190.014.514
25.262.271	0.000	36,306 725	28.293.008	8.811.026	195,679 000	153,731.546	207,765.280	189,681.378
25.258.590	0 000	36,356.619	28,300.500	8.807.779	196,252.000	154.203.936	208,269.682	187,974.841
25,276.916	0.000	36,280.674	28.263.394	8.815.663	195,679.000	154.535.215	207.896.588	188,406.560
25.261.153	0.000	36.252.900	28,262.457	8.828.395	195.871.000	153,808.564	207.846.930	189.922.008
25.249.749	0.000	36.308.996	28,207.960	8.805.568	196,010.000	154,404 925	208.405.128	189.165.670
25.304.347	0.000	36.324.784	28,251.742	8.797.929	196,470.000	155,288.498	208.838.620	190.464.559
25.302 875	0.000	36.283.335	28.241.186	8,818 175	196.257.000	155.671 923	208.736.626	189,955.160
25.272.742	0.000	36,312.735	28.251.725	8,798 116	195.857.000	153.975.929	208.243.572	189.654.478
25.231.219	0.000	36.298.098	28.248.160	8.820.415	195.683.000	154,489.521	208,166.818	188,865.137
25,299.953	0 000	36,276.083	28.237.762	8 815.744	196,216.000	154,494.879	208.698.931	189,663 231
25.264.474	0.000	36.279.293	28.233.135	8 816 048	195,250.000	154,145.814	207,670.453	188,519.748
25.261.494	0 000	36,284.554	28.243 776	8,800.401	195,033.000	153.486.437	207,237.134	188.520.659
25.290.552	0.000	36.365.647	28.282.029	8.827.462	195,110.000	153,200 193	207.236.764	190,041.364
25,253.474	0.000	36,273.814	28,251.814	8.824.258	196,023.000	154.807.253	208,409.765	190,201.046
25.245.288	0.000	36,264.586	28,277.832	8,804.185	195,764.000	154.001.773	208,434.945	191,676.778
25.246.443	0.000	36,337.363	28,248.668	8,776.486	195.919.000	154.008 516	208,375.172	189,397.380
25.269.465	0.000	36,317.752	28,281 966	8.807.448	196.416.000	154,910.864	209.002.743	190.289.200
25.307.683	0.000	36.324.942	28.256.094	8.818.420	196,270.000	154,694.737	209,128.395	190.508.853
25.248.033	0 000	36.313.960	28.269.681	8.807 841	196,324.000	154,841.506	208,843.708	191,233.619
25,248.924	0 000	36.308.795	28.247.400	8,831.225	195.677.000	154.335.804	208,142.441	189,195.355
25,255 981	0.000	36 314.071	28.228.157	8,826.950	195.947 000	154,402.208	208.274.774	190,879.911
25.289.714	0.000	36.308.684	28.247.470	8.823.030	195,460 000	154,223.053	207.856.825	189,284.782
25.278.930	0.000	36.317.102	28.261.451	8,794 695	195,532.000	154.920.916	207.730.925	190,145.762
25.268.595	0.000	36,278.503	28.261 701	8,814.407	196.371.000	154.938.979	208,637.189	191,846.681
25,263.724	0.000	36.309 091	28,273.930	8.792.415	196.659.000	154.941.960	209.116.036	191.606.166
25.272.205	0.000	36.247 938	28.243.068	8,794.112	196.108.000	154,558.713	208.720.417	189.941.354
25.246.645	0.000	36.240.031	28.288.244	8.786.221	195,659.000	153,737.393	208.084.776	188,932.543
25 246.089	0 000	36 251.373	28.281.330	8.805.146	195,814.000	155,018 118	208.337.073	191,096.214
25.262.035	0.000	36.268.141	28,245.101	8,807.318	195.947.000	154,738 583	208.294.014	188,886.455
25.272.064	0.000	36,305 132	28.252.568	8,836.818	195.439 000	153.937.055	207.938.054	188.939.491
25.288.917	0.000	36.297.509	28.273.889	8.812.856	195.509.000	154.313.109	207.830.524	188.610.608
25.266.932	0 000	36.308.615	28.269 524	8.813.532	195,930.361	154,481.413	208,290.534	189.981.302
25,264.474	0.000	36.312.735	28.270 010	8,813.203	195.989.000	154,489 521	208,300.024	189.955 160
19.862	0.000	30 411	23.289	14.645	390 719	557.864	458.698	977.127
15.994	0.000	23.552	18.778	11.978	319.282	458 399	365 552	802.145
0 063	0.000	0.065	0.066	0.136	0 163	0.297	0.175	0.422

Incinerator FG	HP Fuel Gas	LP Fuel Gas	HP Flare	LP Flare	Stabiliser Feed	Stabilised Cond	Produced Water
Stream 20	Stream 29	Stream 33	Stream 36	Stream 40	Stream 31	Stream 32	Stream 30
Nm^3/h	Nm^3/h	Nm^3/h	Nm^3/h	Nm^3/h	Nm^3/h	Nm^3/h	Nm^3/h
57.811	3,409.054	446.693	392.059	468.650	1,489.689	972.841	179.122
57.863	3,412.741	445.843	394.761	481.630	1,485.455	980.316	141.805
57.859	3,453.465	445.014	393.369	480.502	1,485.794	972.679	67.171
57.800	3,399.539	444.988	398.151	493.435	1,482.915	973.004	174.147
57.808	3,410.643	444.173	395.036	489.608	1,475.972	979.016	68.415
57.890	3,435.870	444.885	384.392	477.154	1,487.318	971.216	115.683
57.832	3,431.209	445.277	371.139	484.936	1,477.835	984.703	42.293
57.900	3,415.540	446.471	386.369	452.322	1,485.794	981.128	78.366
57.645	3,412.169	447.033	394.424	453.027	1,483.931	979.016	93.293
57.766	3,432.992	445.549	393.082	478.012	1,483.593	983.403	44.781
57.882	3,439.991	445.634	390.830	490.180	1,486.980	976.091	69.659
57.897	3,379.034	445.266	394.995	480.264	1,480.545	977.391	51.000
57.907	3,411.784	445.761	395.052	496.403	1,481.899	975.116	52.244
57.918	3,425.922	444.806	390.888	476.584	1,487.149	971.054	106.976
57.885	3,419.320	445.097	393.369	467.453	1,483.423	977.878	21.146
57.821	3,409.731	445.816	392.780	456.825	1,488.842	975.116	73.390
57.836	3,425.126	446.216	394.502	460.846	1,492.398	975.116	124.391
57.789	3,393.713	446.379	394.635	460.865	1,480.545	978.853	139.317
57.808	3,414.264	445.070	398.450	478.253	1,487.996	976.741	113.195
57.876	3,404.192	446.330	386.788	482.027	1,491.382	972.841	94.537
57.881	3,405.657	446.464	385.495	494.832	1,487.318	976.091	135.586
57.838	3,432.524	446.086	374.811	494.708	1,483.085	975.278	78.366
57.881	3,428.994	445.676	397.113	485.197	1,488.673	971.704	116.927
57.867	3,411.326	446.548	398.220	474.453	1,479.359	981.941	78.366
57.844	3,423.561	446.152	390.292	451.708	1,485.625	983.078	62.195
57.816	3,408.369	447.260	387.230	452.092	1,482.238	980.641	93.293
57.709	3,391.832	445.468	390.746	452.132	1,484.439	984.053	32.342
57.774	3,445.551	446.072	385.389	492.829	1,487.318	981.778	51.000
57.772	3,441.648	445.988	399.108	482.845	1,485.117	974.141	74.634
57.785	3,413.137	446.094	402.742	498.576	1,478.174	980.803	80.854
57.861	3,438.259	445.595	388.297	486.249	1,488.673	975.603	84.586
57.791	3,424.184	446.059	393.590	485.431	1,486.641	976.416	105.732
57.821	3,394.560	446.940	397.562	470.396	1,484.439	981.778	51.000
57.832	3,418.688	446.583	401.431	470.045	1,488.842	971.379	68.415
57.866	3,413.257	446.469	391.134	465.244	1,488.504	975.603	77.122
57.832	3,412.809	445.047	389.088	473.809	1,476.819	979.178	29.854
57.690	3,414.724	446.198	397.156	475.560	1,484.101	965.529	57.220
57.583	3,411.307	446.051	381.922	482.303	1,483.085	975.441	77.122
57.696	3,398.794	446.648	399.468	482.769	1,484.439	973.816	42.293
57.844	3,432.923	445.325	402.332	459.035	1,482.238	970.729	82.098
57.802	3,424.438	446.661	401.693	427.680	1,481.053	974.303	109.464
57.743	3,390.024	447.529	409.729	468.206	1,480.037	981.291	93.293
57.927	3,391.554	447.913	389.806	460.772	1,493.245	977.553	59.707
57.939	3,400.079	446.636	394.884	474.105	1,486.980	981.291	83.342
57.840	3,394.438	446.107	395.368	476.161	1,492.398	985.353	27.366
57.923	3,406.380	445.125	395.739	484.175	1,489.181	976.578	104.488
57.858	3,413.223	445.506	393.548	496.541	1,484.947	975.928	129.366
57.878	3,402.487	446.334	389.918	489.256	1,482.746	980.316	23.634
57.872	3,405.388	445.294	389.809	480.283	1,489.012	980.478	53.488
57.772	3,395.735	446.775	396.036	467.009	1,490.028	978.528	21.146
57.922	3,401.097	448.517	400.630	476.189	1,482.577	987.953	88.317
57.993	3,415.698	447.643	404.117	465.881	1,486.641	982.591	18.659
57.726	3,405.391	446.228	404.245	467.410	1,494.431	975.278	55.976
57.916	3,416.008	445.550	396.930	488.611	1,486.472	980.316	121.903
57.885	3,423.767	446.086	392.814	483.780	1,481.561	975.928	85.830
57.884	3,451.584	445.201	393.635	480.354	1,494.600	971.054	150.513
57.869	3,402.566	445.525	399.711	482.993	1,485.625	978.528	95.781
57.893	3,403.179	446.802	397.311	457.373	1,486.302	983.241	58.464
57.740	3,423.791	447.411	392.984	444.046	1,483.593	978.691	145.537
57.672	3,446.114	448.164	400.391	469.388	1,486.980	983.890	111.952
57.880	3,387.510	446.651	395.902	479.458	1,483.593	986.003	34.829
57.831	3,414.735	446.110	393.826	474.735	1,485.419	977.764	82.016
57.844	3,412.809	446.086	394.502	477.154	1,485.625	977.553	78.366
0.077	16.604	0.871	6.600	14.519	4.123	4.507	38.192
0.059	13.075	0.675	4.767	11.552	3.241	3.709	30.296
0.103	0.383	0.151	1.208	2.421	0.218	0.379	38.659