|  |  |
| --- | --- |
| Logo_new_black | |
| **WA Engineering Operations**  KWINANA SGA SURFACE AREA CONTROL  **March 18**  **1st Edition** | |
|  |  |

Copyright Alcoa World Alumina - Australia 2018

This document and all the information and ideas contained within are the property of   
Alcoa World Alumina - Australia and are confidential. Neither this document nor any part thereof, nor any information contained in it may be disclosed or furnished to others without the prior written consent of   
Alcoa World Alumina - Australia.

# TITLE PAGE

**TITLE : KWINANA SGA SURFACE AREA CONTROL**

**AUTHOR :** David Zhang

**DATE :** January 2009

**APPLIES TO :** OC4 Technical, Production and Management Personnel

**KEY WORDS :** Surface Area, Calcination

# Executive Summary

SGA surface area control at Kwinana is currently slow and inaccurate due to the lack of quantitative understanding of the relationships between surface area and the three major process variables: furnace temperature, D4 temperature and gas flow rate. To address this problem experimental trials were conducted on units 5 to 8 and the samples analysed to develop models between these variables and SGA surface area. Units 3 was unavailable due to ongoing α-phase issues and unit 4 was assigned to special production runs.

Strong correlations between the two temperatures and surface area were found and regression models were developed for calciner units 5 to 8. These not only confirmed the inverse relationship between temperature and surface area but also quantified these relationships. Correlations for gas flow rate could not be found due to the inability to manipulate gas flow rate which would interfere with production.

The following table summarises the models developed, listing the range of conditions for which they are applicable. Detailed graphical representations of the models can be found in the results chapter.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Unit | Temperature used for control | Regression equation | Applicable range of calciner conditions\* | Response in surface area per 10 oC increase |
| 5 | Furnace | *SA* = 250 – 0.18 *T*f | 930 oC ≤ *T*f ≤ 990 oC  700 oC ≤ *T*D4 ≤ 740 oC | 1.6 – 1.9 m2/g decrease |
| D4 | *SA* = 165 – 0.11 *T*D4 | 930 oC ≤ *T*f ≤ 970 oC  700 oC ≤ *T*D4 ≤ 770 oC | 0.8 – 1.4 m2/g decrease |
| 6 | Furnace | *SA* = 210 – 0.14 *T*f | 940 oC ≤ *T*f ≤ 990 oC  740 oC ≤ *T*D4 ≤ 760 oC | 1.2 – 1.6 m2/g decrease |
| D4 | *SA* = 150 – 0.10 *T*D4 | 930 oC ≤ *T*f ≤ 950 oC  700 oC ≤ *T*D4 ≤ 750 oC | 0.95 – 1.05 m2/g decrease |
| 7 | Furnace | *SA* = 475 – 0.37 *T*f | 1040 oC ≤ *T*f ≤ 1100 oC  800 oC ≤ *T*D4 ≤ 870 oC | 3.4 – 4.0 m2/g decrease |
| D4 | *SA* = 300 – 0.26 *T*D4 | 1040 oC ≤ *T*f ≤ 1080 oC  790 oC ≤ *T*D4 ≤ 890 oC | 2.1 – 3.1 m2/g decrease |
| 8 | Furnace | *SA* = 215 – 0.15 *T*f | 930 oC ≤ *T*f ≤ 990 oC  630 oC ≤ *T*D4 ≤ 690 oC | 1.1 – 1.7 m2/g decrease |
| D4 | *SA* = 170 – 0.15 *T*D4 | 940 oC ≤ *T*f ≤ 960 oC  620 oC ≤ *T*D4 ≤ 700 oC | 1.3 – 1.6 m2/g decrease |

\*Applicable at gas flow rates above 80% of the maximum gas flow rate

It is proposed that the regression models be used together with the information in the table to improve control of SGA surface area at Kwinana. In particular, the last column in the table should be used as a ‘rule of thumb’ in conjunction with the daily refinery sample for surface area control. It should be emphasised that the calciner conditions should fall within the applicable range listed above before the model can be applied accurately. The models can still be applied outside these ranges with a penalty in accuracy.

# Acknowledgements

The author would like to thank the following people for their invaluable contribution to the project. Without their help and knowledge this work would not have been completed.

*Ben Rajasigamany*

Project supervisor.

*Ian Thompson*

Introduction and instruction on sample collection.

*Nicole Ferrel*

Laboratory analysis of the numerous SGA samples.

*OC4 Group Leaders and Shifts*

Making the necessary adjustments on unit temperatures for the trial.

*Greg Peterson*

Review and suggestions on the stastical analysis.

# Table of Contents

TITLE PAGE 3

Executive Summary 4

Acknowledgements 5

Table of Contents 6

1 Introduction 9

2 Project Scope 11

Problem Statement 11

Project Objectives 11

Process Background 12

SGA Surface Area 12

3 Experimental 14

General Approach 14

Procedure 14

Varied Temperature Trials 14

‘LONG TERM’ Fixed temperature trials 15

Sample Collection & Data Extraction 15

Sample Analyses 16

Assumptions 16

4 Results & Discussion 17

Varied Temperature Trials 17

Unit 5 17

UNIT 6 19

UNIT 8 20

Unit 7 22

‘Long Term’ Fixed Temperature Trials 26

Multivariable Analysis 27

5 Conclusion 28

6 Recommendations 29

Appendices 31

Appendix A: Sampling Schedule and Results 31

Appendix B: Detailed Statistical Analysis Procedure 41

Appendix C: Regression Coefficient Intervals 2

# 1 Introduction

Kwinana refinery currently controls its smelter grade alumina (SGA) surface area to pre-defined targets by ad-hoc adjustments to process variables. Although the qualitative relationship between these variables and surface area is known, the quantitative impact and interaction between these variables is not.

SGA surface area control has last been investigated at Kwinana in 2005. That project assessed calciner units 5 and 8 with only a limited run of twelve samples in total. Although correlations were developed, it was recommended that further investigation was necessary.

In response a comprehensive project investigation consisting of over 280 samples on calciner units 5 to 8 (units 3 and 4 being unavailable) was carried out to determine these unknown relationships and to develop more comprehensive and reliable correlations.

This report documents the project and presents the findings along with recommendations to achieve efficient surface area control. The reasoning behind the approach, procedure and data analysis involved in the project is also provided to supplement the results and aid future investigations.

# 2 Project Scope

## Problem Statement

The surface area of SGA is an important quality parameter and must be kept within defined specifications for ALCOA’s customers. It is therefore crucial to be able to accurately and efficiently control surface area to ensure refinery profitability.

The main process variables which affect the surface area of SGA are furnace temperature, D4 temperature, gas flow rate and holding vessel level. The current knowledge is limited to the understanding that there is an inverse relationship between the temperatures SGA is exposed to during calcination and its surface area. However, this relationship has not yet been quantified. Furthermore, changes in more than one of these variables routinely occur in the refinery, and the effect of the interaction between changes in multiple variables is also unkown. To complicate the problem further there are 6 calciner units at Kwinana and each unit exhibits its own unique characteristics and different units produce SGA with different surface areas even when running at the same nominal conditions.

As a result, the surface area of SGA product at Kwinana can and does vary on an hourly basis. The strategy currently employed to stay within production specification utilises calibration with lab samples. A sample from each calciner unit is taken daily and analysed for surface area. The temperatures are then adjusted or kept the same depending on the result. Gas flow rate is not normally adjusted as it is usually dictated by production capacity.

Such a strategy involving guesswork is inefficient and inaccurate. Due to a large feedback loop delay, the response time is cumbersome. Out of specification surface areas can at best be rectified by the next shift, and often longer if the initial adjustments fail to bring the surface area within specification. In addition, there is no way of ascertaining the surface area accurately without lab analysis and so SGA surface area is unknown in the interim between daily samples.

## Project Objectives

In order to address the current issues in surface area control the following objectives were pursued:

* Quantify the effect of furnace temperature, D4 temperature and gas flow rate[[1]](#footnote-1) SGA surface area for all calciners
* Develop a model which can accurately predict SGA surface area based on given values of these variables for all calciners
* Determine the impact of interaction of these variables on SGA surface area

It was also envisaged that the findings of this project could be used to aid the work being conducted on the Calcination Advanced Controller.

## Process Background

Alumina is refined from bauxite ore at the Kwinana refinery via the Bayer Process. The process can be broken down into four main stages:

1. Milling & Digestion – the bauxite ore is ground before its alumina content is dissolved by mixing with a caustic solution.
2. Clarification – the insoluble residues are separated from the mixture.
3. Precipitation – the dissolved alumina is recovered as hydrate crystals (Al2O3.3H2O or gibbsite) via precipitation seeding.
4. Calcination – the crystals are exposed to high temperatures to drive off the physically and chemically bonded moisture to produce alumina capable of being smelted.

The surface area of the SGA is determined during the calcination stage of the Bayer Process. The temperatures to which the hydrate is exposed affects the final surface area. The higher the temperatures and the harder the hydrate is calcined, the lower the surface area and vice versa. A general overview of this stage provides a useful context to understanding how the variables affect surface area.

At this stage, the process stream is conveyed through a number of fluidized vessels pneumatically. Firstly the feed slurry of caustic solution and hydrate crystals is deliquored and washed on filters to reduce the moisture content and impurities, particularly soluble soda. The filtered hydrate then passes through the first cyclone, a drier, and then a second cyclone before reaching the furnace. The cyclones classify the hydrate particles by size and finer particles are transferred to a multiclone and electrostatic precipitator for dust control. Contact with hot gases reaching temperatures of 400 – 450 oC in the ductwork and drier partially calcines the coarser hydrate, removing the free moisture and two of the three chemically bonded water molecules.

In the furnace the partially calcined hydrate is further heated to temperatures of 950 – 1100 oC by the combustion of heated air and fuel gas. It then passes into the holding vessel to ensure the third water molecule is driven off. Finally the calcined SGA passes from the holding vessel, through the D4 stack to the cooling section. D4 stack temperatures typically vary from 600 – 800 oC. In the cooling section, a further series of cyclones and a fluid cooler bring the SGA temperature down to 85 – 95 oC via counter-flow cooling with combustion air before it is discharged onto conveyor belts for loading or storage.

The entire stage takes approximately 30 to 40 minutes to complete from start to finish.

In regards to SGA surface area, an important process bypass during the calcination stage is the hydrate bypass. This process flow line conveys part of the hydrate from the drier directly to the D4 stack so that it is not exposed to the high temperatures in the furnace and holding vessel. This uncalcined hydrate has a greater surface area and increases the overall average surface area of the final SGA product when mixed with the calcined hydrate in the D4 stack. It should be noted that this bypassed hydrate still undergoes partial calcination to some extent due to heating in the D1 stack. The hydrate bypass is used as a cost efficient method to achieve desired surface areas and hence the D4 temperature is an important focus area for this project.

## SGA Surface Area

The changes in SGA surface area can be attributed to two major phenomena which occur during calcination:

1. Increase in surface porosity due to loss of chemically bonded water molecules
2. Changes in pore structure due to calcination temperature and formation of α-phase alumina at high temperatures which has a lower surface area than hydrate

These phenomena are governed by the temperature to which the hydrate is exposed and the length of time for which it is exposed. Hence the major variables under consideration for this project are as mentioned above:

* Furnace temperature
* D4 temperature (affected by hydrate bypass)
* Gas flow rate (related to temperature and throughput of hydrate and hence the exposure period)
* Holding vessel level (related to exposure period)

# 3 Experimental

## General Approach

Experimental trials were conducted across all available calciners[[2]](#footnote-2) from December 2008 to January 2009. Two different approaches were taken, each suited to investigating a particular facet of the project:

1. Varied Temperature Trials

Samples were taken at varying furnace temperatures or D4 temperatures whilst the other temperature was held constant. This approach was primarily to investigate the effect of temperature on SGA surface area. Although sampling was conducted wherever possible at the same gas flow rates, this variable did fluctuate. This is not desirable for investigating the effect of temperature, however, it did allow for additional analysis on the effect and interaction of gas flow rate.

1. ‘Long Term’ Fixed Temperature Trials

Calciner temperatures were held constant whilst gas flow rate changed to investigate in more detail the effect of gas flow rate on SGA surface area.

## Procedure

### Varied Temperature Trials

1. One sample run of furnace temperature would consist of:

* Varying the furnace tempearature across a 50 – 60 oC range (coinciding with the typical operating limits of the unit) with individual step sizes of 10 oC whilst the D4 temperature was held constant. See **Appendix A** for the detailed sampling schedule and results for each calciner unit.
* Three samples taken at each different furnace temperature 20 minutes apart from each other

Note: The sampling temperatures were taken in a random order to reduce the impact of any underlying effects, particularly time dependent effects

* After each step adjustment a 3 hour period was allowed for the unit to equilibrate
* This allows for approximately 5 turnovers of product

1. A second furnace temperature run would be conducted at a new constant D4 temperature
2. Sample runs of D4 temperature would follow the same procedure, except that D4 temperature would be varied and furnace temperature held constant
3. Gas flow rate was left uncontrolled and did change according to production demands. In reality the units operated at maximum gas for the majority of the trials and samples were taken at constant gas flow rates wherever possible.
4. The operating temperatures sampled for each unit were selected to ensure that a ‘square’ of sampling points would be achieved (using the total 4 runs) in the furnace temperature and D4 temperature plane.
5. This allows not only single variable analysis for each run to obtain correlations between SGA surface area and either furnace temperature or D4 temperature, but also allows for multivariable and interaction analysis between SGA surface area and both furnace temperature and D4 temperature

Two methods were utilised to capture the effect of gas flow rate:

* Fluctuations during each run of furnace temperature changes or D4 temperature changes were examined
* ‘Long Term’ Fixed Temperature trials (see below)

### ‘LONG TERM’ Fixed temperature trials

* Units 5 and 6[[3]](#footnote-3) were left at a fixed furnace temperature and a fixed D4 temperature each for over a week
* Three samples were taken during the day at 3 hour intervals, and the daily 2:00 am refinery sample data was also used in the analysis
* Again gas flow rate was left uncontrolled due to refinery demands, but changes would now be captured at consistent temperatures

## Sample Collection & Data Extraction

After each variable was set at the required level by the operators and the unit allowed to equilibrate the SGA product would be sampled from the cooler discharge of the relevant unit in the following manner:

* The sampling tap was opened to allow a steady stream of SGA product to run
* Stream was left to run for 15 seconds to ensure all the SGA within the tap piping had passed so that the sample would represent what had recently been calcined
* The sample was then taken using a wide-mouthed 50 mL container and a multi-cut technique
* The process flow was cut 5 times over a period of 10 seconds to give a composite of 5 samples
* For the Varied Temperature Trials a second and third sample were taken after 20 minute breaks

Despite being set at the nominal values for the trial, inevitably the actual furnace temperature, D4 temperature and gas flow rate would deviate. The actual values were recorded for each sample in the following manner:

* The instantaneous value of the variable at 30 second intervals was extracted using PHD over a period of 2 hours[[4]](#footnote-4) immediately prior to the time the sample was taken
* The mean value of the 240 instantaneous values was calculated and recorded as the actual value for the variable for that sample

The reasoning for following the method above is as follows:

* 30 second intervals were chosen as a compromise between capturing fluctuations and heavy computation for shorter intervals
* A 2 hour period gives more than enough time to ensure unit has reached equilibrium so that the value calculated for the variables is indicative of the true conditions the SGA was calcined at
* The 2 hour period is prior to the sample being taken because the conditions afterwards are irrelevant. What needs to be looked at are the average temperatures the sample was being calcined at and not the average temperature at which the sample was taken from the cooler discharge.
* For the Varied Temperature Trials the mean of the values for the process variables and the lab analysed SGA surface area for the three samples was taken. This was done in an effort to reduce the variability in the trial due to inherent calciner instability. It was these average values that were used to develop the correlations.

## Sample Analyses

Each SGA sample was analysed at the on site laboratory for surface area using Gemini 2360 analysers. The standard deviation for lab analysed surface area results is 0.7 m2/g.

## Assumptions

Due to the weir discharge design of the holding vessels in units 5 to 8 holding vessel level was assumed to be at a constant level not factored into the model. It should still be noted that the holding vessel level value given on ROT did fluctuate by up to ±2 % on the units during the trials.

# 4 Results & Discussion

## Varied Temperature Trials

The data collected from these trials were collated and then statistically analysed in Minitab. Individual regression analysis was conducted for each separate run of temperature variation to develop a correlation between SGA surface area and the manipulated process variable (either furnace temperature or D4 temperature). Multivariable analyses were also pursued with less successful correlations. These shall be briefly discussed towards the end of the chapter.

A detailed description of the data analysis procedure using the data collected for calciner unit 5 as an example can be found in **Appendix B**. In general, the same procedure was adopted for analysing the results for each unit. The report indicates wherever this procedure was departed from and provides an explanation as to why it was altered.

This section provides the final results of the data analysis using the mean data and selected results using the raw data to illustrate short-term surface area variability.

### Unit 5

*Variation of Furnace Temperature*

**Figure 4.1** Regression Analysis for Unit 5 Variation of Furnace Temperature

***Mean Data***

|  |  |
| --- | --- |
| Regression Equation:  *SA* = 249 – 0.177 *T*f | |
| S | 1.181 |
| R2 (adj) | 94.6% |
| SE of constant | 20.25 |
| SE of coefficient | 0.021 |



*T*D4 = 710 oC, *G* ≈ 3400 SCM/h

The inverse relationship between surface area and furnace temperature can clearly be seen in **figure 4.1**. Quantitatively, the coefficient in the regression equation indicates that for every 10 oC increase in furnace temperature there is an expected 1.8 m2/g decrease in SGA surface area. It should be kept in mind that this correlation is applicable only at a D4 temperature of 710 oC and a gas flow rate of 3400 SCM/h.

However, there is evidence from the other results[[5]](#footnote-5) in this trial that the correlations obtained are applicable over a wider range of calciner unit conditions.

*Variation of D4 Temperature*

**Figure 4.2** Regression Analysis for Unit 5 Variation of D4 Temperature – Run 1

***Mean Data***

|  |  |
| --- | --- |
| Regression Equation:  *SA* = 163 – 0.113 *T*D4 | |
| S | 2.052 |
| R2 (adj) | 58.2% |
| SE of constant | 29.24 |
| SE of coefficient | 0.040 |

***Raw Data***

|  |  |
| --- | --- |
| Regression Equation:  *SA* = 162 – 0.113 *T*D4 | |
| S | 2.052 |
| R2 (adj) | 47.0% |
| SE of constant | 20.56 |
| SE of coefficient | 0.028 |



*T*f = 960 oC, *G* ≈ 4300 SCM/h

**Figure 4.3** Regression Analysis for Unit 5 Variation of D4 Temperature – Run 2

***Mean Data***

|  |  |
| --- | --- |
| Regression Equation:  *SA* = 165 – 0.116 *T*D4 | |
| S | 0.063 |
| R2 (adj) | 99.9% |
| SE of constant | 1.84 |
| SE of coefficient | 0.002 |



*T*f = 940 oC, *G* ≈ 4250 SCM/h

The figures on the previous page confirm the inverse proportional relationship between D4 temperature and surface area. An important feature to note is that the coefficients in both regression equations are extremely similar. This suggests that the magnitude of the affect of D4 temperature on surface area is independent of the furnace temperature for at least the furnace temperatures used in these two sample runs. The coefficients indicate that for every 10 oC increase in D4 temperature there is an expected 1.1 – 1.2 m2/g decrease in mean surface area.

Additionally, **figure 4.2** illustrates the short-term variability in surface area. The individual results for the three repeat samples taken at each step adjustment are shown with black markers together with the mean result of the three samples shown with a red marker. This variation should always be kept in mind when controlling SGA surface area. It is important to distinguish between what is inherent variation and what is a real change in surface area provoked by differing unit conditions. Using the raw data for all units, the estimated individual measurement uncertainty (*s*p) for SGA surface area was calculated to be 1.58 m2/g.

The results for unit 5 also demonstrate that changes in furnace temperature have a greater impact in terms of magnitude on the surface area then changes in D4 temperature. Numerically, a given increase in furnace temperature illicits about a 50% greater decrease in surface area than the same increase in D4 temperature.

### UNIT 6

Unit 6 behaves in much the same manner as unit 5. Again the results confirm that surface area is inversely related to both furnace temperature and D4 temperature. Additionally, the results also show that furnace temperature has about a 50% greater effect on surface area with a 10 oC change in furnace temperature producing a 1.4 m2/g decrease in surface area whilst the same change in D4 temperature will only decrease surface area by about 1 m2/g.

Although the correlation between the two temperatures and surface area for unit 6 were very strong (adjusted R2 values were both above 85%) there were not enough usable sample runs on unit 6 to provide further evidence on whether these correlations could be applicable over a wider range of unit conditions.

*Variation of Furnace Temperature*

**Figure 4.4** Regression Analysis for Unit 6 Variation of Furnace Temperature

***Mean Data***

|  |  |
| --- | --- |
| Regression Equation:  *SA* = 209 – 0.142 *T*f | |
| S | 1.087 |
| R2 (adj) | 85.4% |
| SE of constant | 24.85 |
| SE of coefficient | 0.026 |



*T*D4 = 750 oC, *G*  ≈ 4250 SCM/h

*Variation of D4 Temperature*

**Figure 4.5** Regression Analysis for Unit 6 Variation of D4 Temperature

***Mean Data***

|  |  |
| --- | --- |
| Regression Equation:  *SA* = 151 – 0.099 *T*D4 | |
| S | 0.172 |
| R2 (adj) | 99.0% |
| SE of constant | 3.63 |
| SE of coefficient | 0.005 |



*T*f = 940 oC, *G* ≈ 4200 SCM/h

### UNIT 8

*Variation of Furnace Temperature*

**Figure 4.6** Regression Analysis for Unit 8 Variation of Furnace Temperature – Run 1

***Mean Data***

|  |  |
| --- | --- |
| Regression Equation:  *SA* = 238 – 0.165 *T*f | |
| S | 0.206 |
| R2 (adj) | 99.5% |
| SE of constant | 6.72 |
| SE of coefficient | 0.007 |

***Raw Data***

|  |  |
| --- | --- |
| Regression Equation:  *SA* = 237 – 0.165 *T*f | |
| S | 1.040 |
| R2 (adj) | 85.6% |
| SE of constant | 19.53 |
| SE of coefficient | 0.020 |



*T*D4 = 675 oC, *G* ≈ 4550 SCM/h

**Figure 4.7** Regression Analysis for Unit 8 Variation of Furnace Temperature – Run 2

***Mean Data***

|  |  |
| --- | --- |
| Regression Equation:  *SA* = 207 – 0.136 *T*f | |
| S | 1.530 |
| R2 (adj) | 77.1% |
| SE of constant | 30.83 |
| SE of coefficient | 0.032 |



*T*D4 = 646 oC, *G*  ≈ 4050 SCM/h

Unlike the D4 temperature correlations for unit 5 which exhibited almost the same regression coefficient, the two furnace temperature correlations for unit 8 shown in **figure 4.6** and **figure 4.7** have slightly differing coefficients of - 0.165 m2/g/oC and - 0.136 m2/g/oC . This indicates that the impact of furnace temperature on surface area is different and not independent of the other variables.

The context of these sample runs must be considered. For unit 5, the D4 temperature runs were conducted at very similar gas flow rates (around 4250 SCM/h) but of course at different furnace temperatures. For unit 8, the two furnace temperature runs were conducted with noticeably different gas flow rates – 4050 SCM/h and 4550 SCM/h – and this may explain the difference. Thus it is still sensible to propose that the effect of furnace temperature and D4 temperature on surface area are independent enough when operating within normal refinery temperatures (*T*f = 930 – 1000 oC, *T*D4 = 650 – 750 oC) to allow the correlations to apply generally as long as the gas flow rate is maintained.

Also, it must be kept in mind that there is an uncertainty associated with each regression coefficient. Rather than considering them to be exact the coefficient should be considered as capable of ranging between values in an interval defined by the standard error of the coefficient. The figure[[6]](#footnote-6) below illustrates these intervals to 2 standard deviations for the regression coefficients for the two unit 8 furnace temperature correlations:

**Figure 4.8** Regression coefficient intervals

This overlap in the intervals provides further evidence that the effect of furnace temperature on surface area is very similar over a range of D4 temperatures and gas flow rates.

*Variation of D4 Temperature*

**Figure 4.9** Regression Analysis for Unit 8 Variation of D4Temperature

***Mean Data***

|  |  |
| --- | --- |
| Regression Equation:  *SA* = 170 – 0.146 *T*D4 | |
| S | 0.206 |
| R2 (adj) | 96.6% |
| SE of constant | 9.03 |
| SE of coefficient | 0.014 |

***Raw Data***

|  |  |
| --- | --- |
| Regression Equation:  *SA* = 170 – 0.145 *T*D4 | |
| S | 1.489 |
| R2 (adj) | 85.6% |
| SE of constant | 10.50 |
| SE of coefficient | 0.016 |



*T*f = 950 oC, *G*  ≈ 4150 SCM/h

The results for the unit 8 D4 temperature run suggest that unit 8 differs slightly from units 5 & 6. In those two units furnace temperature had a greater effect than D4 temperature on surface area. In contrast, for unit 8, both temperatures are expected to affect surface area to a similar degree since the regression equation coefficients are both around - 0.15 m2/g/oC. This may be due to a difference in unit design – unit 8 operates with a hydrate cooler upstream from the D4 stack and the D4 temperature is in fact controlled by the hydrate cooler temperature. The impact of both the hydrate cooler and D4 stack temperatures may result in the appearance that unit 8 D4 temperature has an increased effect on surface area compared to that in units 5 & 6 and explain why its effect is on par with the furnace temperature.

### Unit 7

Unit 7 is unique compared to the other units at Kwinana refinery. It was designed so that the hydrate is conveyed into the furnace at a vertically higher point compared to the other units. This reduces the time the hydrate is exposed to the hot gases while in the furnace (although it still passes through the holding vessel in the same manner). Because of this unit 7 operates at higher temperatures in the furnace, holding vessel and D4 stack in order to achieve similar surface areas as the other units.

*Variation of Furnace Temperature*

An issue encountered with unit 7 that is very likely to be linked to its higher operating temperatures is the difficulty to independently manipulate furnace temperature without affecting the D4 temperature. An increase or decrease in the furnace temperature set point is accompanied with a similar increase or decrease in the actual D4 temperature. The root cause of this is to do with the air flows within the unit, but this aspect of calciner operation is outside the scope of this project.

Consequently, the D4 temperature was not constant during the sample runs varying furnace temperature. Hence the regression analysis was conducted using furnace temperature as the predictor variable and again using D4 temperature as the predictor variable. During the first run the D4 temperature set point was not touched and the actual D4 temperature was allowed to shift on its own according to the adjustments made to the furnace temperature (see **figure A.3** in **Appendix A**).

**Figure 4.10** Regression Analysis for Unit 7 Variation of Furnace Temperature – Run 1

***Using Furnace Temperature as the Predictor Variable –***

***Mean Data***

|  |  |
| --- | --- |
| Regression Equation:  *SA* = 475 – 0.368 *T*f | |
| S | 1.470 |
| R2 (adj) | 96.5% |
| SE of constant | 33.66 |
| SE of coefficient | 0.031 |

***Using D4 Temperature as the Predictor Variable –***

***Mean Data***

|  |  |
| --- | --- |
| Regression Equation:  *SA* = 336 – 0.305 *T*D4 | |
| S | 0.281 |
| R2 (adj) | 99.9% |
| SE of constant | 4.12 |
| SE of coefficient | 0.005 |



*G* ≈ 3950 SCM/h

The higher adjusted R2 value when using D4 temperature as the predictor variable suggests that D4 temperature is a better variable to use to predict SGA surface area for unit 7. Having said that, both furnace and D4 temperature appear to be excellent predictors of surface area and either correlation could be used.

These results should be compared to those of the second run, where the D4 temperature set point was manipulated in an attempt to maintain a constant D4 temperature whilst the furnace temperature varied. Unfortunately this involved a lot of guesswork and the D4 temperature still varied during the second run.

**Figure 4.11** Regression Analysis for Unit 7 Variation of Furnace Temperature – Run 2

***Using Furnace Temperature as the Predictor Variable –***

***Mean Data***

|  |  |
| --- | --- |
| Regression Equation:  *SA* = 134 – 0.058 *T*f | |
| S | 7.188 |
| R2 (adj) | 0.0% |
| SE of constant | 188.4 |
| SE of coefficient | 0.175 |

***Using D4 Temperature as the Predictor Variable –***

***Mean Data***

|  |  |
| --- | --- |
| Regression Equation:  *SA* = 266 – 0.222 *T*D4 | |
| S | 0.949 |
| R2 (adj) | 97.9% |
| SE of constant | 12.72 |
| SE of coefficient | 0.015 |



*G*  ≈ 3800 SCM/h

For the second sample run D4 temperature clearly stands out as the best predictor for surface area. In fact, the analysis shows no correlation between furnace temperature and surface area. Even with the striking result found at 1080 oC furnace temperature removed there is an extremely poor correlation.

Interestingly this sample run was intended as a variation of furnace temperature run. As mentioned above, the difference between this run and the first run was that the D4 temperature set point was also manipulated rather than allowed to self-adjust with the furnace temperature. We can infer that unit 7 is far more predictable when varying furnace temperature if the D4 temperature is left to vary by itself (although the setpoint will remain the same). This seems to allow the unit to find its own equilibrium. In either case, D4 temperature is the better predictor and it is this variable that should be used to control surface area for unit 7.

*Variation of D4 Temperature*

Strangely, it is possible on unit 7 to manipulate D4 temperature independently of furnace temperature. This is because the D4 stack is down stream in the process path relative to the furnace, and altering the D4 stack temperature by increasing or decreasing flow through the bypass valve will not affect the furnace temperature. Thus for these sample runs unit 7 behaved like the other units and furnace temperature was held constant whilst D4 temperature was varied.

**Figure 4.12** Regression Analysis for Unit 7 Variation of D4 Temperature – Run 1

***Mean Data***

|  |  |
| --- | --- |
| Regression Equation:  *SA* = 318 – 0.284 *T*D4 | |
| S | 1.855 |
| R2 (adj) | 93.7% |
| SE of constant | 30.23 |
| SE of coefficient | 0.037 |

***Raw Data***

|  |  |
| --- | --- |
| Regression Equation:  *SA* = 317 – 0.283 *T*D4 | |
| S | 2.722 |
| R2 (adj) | 85.5% |
| SE of constant | 25.55 |
| SE of coefficient | 0.031 |



*T*f = 1050 oC, *G* ≈ 3850 SCM/h

**Figure 4.13** Regression Analysis for Unit 7 Variation of D4 Temperature – Run 2

***Mean Data***

|  |  |
| --- | --- |
| Regression Equation:  *SA* = 283 – 0.242 *T*D4 | |
| S | 1.349 |
| R2 (adj) | 93.8% |
| SE of constant | 26.51 |
| SE of coefficient | 0.031 |



*T*f = 1070 oC, *G*  ≈ 3900 SCM/h

Unit 7 stands out amongst the other units due to the much larger effect the temperature has on surface area. The coefficients in the regression equations are all greater in magnitude than 0.22 m2/g/C. From the first furnace temperature sample run we can infer that, like units 5 & 6, the furnace temperature in unit 7 has a greater impact on surface area.

Once again the regression coefficients are all relatively similar amongst the D4 temperature correlations and supports the use of these correlations over the range of furnace temperatures encountered during the trial.

## ‘Long Term’ Fixed Temperature Trials

These trials were intended to capture the effect of changes in gas flow rate on SGA surface area. The furnace temperature and D4 temperature were left at the same set point throughout the trial. Unfortunately, as can be seen in the results below, the gas flow rates did not vary enough during the period the trial was conducted to enable a reliable correlation to be found between gas flow rate and surface area.

**Figure 4.14** Scatterplot of Gas Flow Rate versus Surface Area for unit 5



*T*f = 960 oC, *T*D4 = 735 oC

**Figure 4.15** Scatterplot of Gas Flow Rate versus Surface Area for unit 6



*T*f = 960 oC, *T*D4 = 735 oC

The experimental design was inadequate in that gas flow rate was not directly controlled, instead it was hoped that it would fluctuate. From a statistical point of view, even if gas flow rate did vary considerably throughout the trial one would not know whether the response in surface area was due to the gas flow rate or some other change that accompanied it. A lesson for the future would be to ensure the experiment involves direct manipulation of the gas flow rate.

### long term surface area variation

The results do however provide a good insight into the variation of surface area due to unit instability despite running at the same configuration of temperatures and gas flow rate.

**Table 4.1** Summary of Statistics for Surface Area of SGA product for units 5 & 6

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  | Mean | SE of Mean | Standard Deviation | Minimum | 1st Quartile | Median | 3rd Quartile | Maximum |
| Unit 5\* | 75.0 | 0.939 | 4.201 | 70.2 | 72.0 | 73.7 | 77.6 | 87.6 |
| Unit 6\* | 73.0 | 0.866 | 2.873 | 67.5 | 69.9 | 74.1 | 74.9 | 76.5 |

\* All values are in units of m2/g

Although we do expect some variation in the surface area (and also variation due sampling and laboratory measurement variation) the large range of surface area values (70.2 – 87.6 m2/g for unit 5 and 67.5 – 76.5 m2/g for unit 6) during these trials support the hypothesis that surface area may also be affected by the actual material passing through the process. The quality of the hydrate received from the precipitation stage of the Bayer process will have undoubtedly varied over the long period during which these units were held at the same conditions and this will have affected the surface area of the final SGA product.

The results indicate that surface area variation occurs both over a very short term (as seen in the raw data) and over a long term. This is not fatal to the correlations developed above since the Varied Temperature trials were conducted before and after the Long Term trials. Despite the long term variation the correlations achieved for temperature and surface area both before and after are all quite strong. Thus the correlations will still be applicable over long time periods in the sense that the response produced for a given change in temperature will be the same (i.e. the regression coefficient will still be applicable) even if the absolute surface area may differ (i.e. the regression constant may not be applicable). For example, a 10 oC furnace temperature increase in unit 5 will still produce a 1.8 m2/g decrease in surface area, although the absolute value of the surface area may change over a month. In this way SGA surface area can still be controlled by reference to the daily refinery sample.

## Multivariable Analysis

Analysing the entire set of data for each unit to obtain a general correlation for SGA surface area as a single function of furnace temperature, D4 temperature and gas flow rate was also attempted. Second degree interaction variables were also considered such as *T*f •*T*D4, *T*f •*G* and *T*D4•G. However no stastically significant correlations were found. There are a number of possible explanations. Firstly there was not enough gas flow rate variaibility in the data. Secondly the design of the trials was aimed at ascertaining the individual effect of one of the temperatures on surface area. It is recommended that a trial specifically designed for assessing the effect of gas flow rate be conducted in the future.

Multivariable analysis utilising only furnace temperature and D4 temperature and not gas flow rate as the predictor variables faired better. The regression results showed that the coefficient for the interaction variable *T*f •*T*D4 was stastistically insignificant compared to the coefficients for the individual temperatures. This confirms that it is far more reliable to control surface area by considering the individual impact of each temperature rather than the impact of their interaction.

# 5 Conclusion

The results of the trial clearly confirm the inverse relationship between unit operating temperatures and SGA surface area. More importantly, the regression analysis has provided stastistically significant correlations[[7]](#footnote-7) between furnace temperature and surface area and D4 temperature and surface area for all units trialed. To complement these correlations, comparison between the results of each sampling run has yielded further findings.

There is strong evidence that the quantitative effect of one temperature on surface area is independent enough of the other temperature and of gas flow rate within the range of operating conditions[[8]](#footnote-8) used in the trial. This range of operating conditions was selected to coincide with the normal operating conditions at the refinery. Thus it should be emphasised that these correlations are only applicable at these conditions.

Admittedly there is a small amount of interaction between the two temperatures and gas flow rate, however this is negligible compared to the direct impact caused by each individual temperature. As pointed out in the previous chapter, this is evident from two features of the results. Firstly, from the relatively similar regression coefficients encountered for furnace temperature at different D4 temperatures and vice versa. Secondly, from the overlap seen in the regression coefficient intervals. Thus the correlations for either temperature could be utilised to allow efficient control of SGA surface area at Kwinana to within ± 1.5 m2/g (± *s*p).

It was also found that for units 5, 6 & 7 that a change in furnace temperature would produce a 50% greater response in surface area then the same change in D4 temperature. Only in unit 8 was the effect of both temperatures equal and it is suggested that this is due to the incorporation of the hydrate cooler in the design of unit 8.

Generally speaking 10 oC increases in furnace temperature would produce an expected 1.4 – 1.8 m2/g decrease in surface area whilst the same increase in D4 tempearture would produce an expected 1.0 – 1.4 m2/g decrease. Unit 7 is exceptional due to its design, and the impact of temperature is greater, with an expected 3.4 – 4.0 m2/g decrease and a 2.1 – 3.1 m2/g decrease in surface area for a 10 oC increase in furnace temperature and D4 temperature respectively.

The long-term trials indicate that even at the same operating conditions the surface area can vary a significant amount over a long time period. However it was explained above[[9]](#footnote-9) that the regression coefficients will still be applicable.

Of equal importance are the learnings taken from conducting the trials. In particular, it was found that the sampling must be done with care and the sampling regime strictly adhered to. The purpose of using the mean data from the three repeat samples was to reduce the impact of the inherent short-term variability in SGA surface area due to calciner instability and fluctuation of the conditions within the unit. The results confirm that a better correlation is obtained when the mean data is used as opposed to the raw data from the repeats.

To allow the correlations developed in this project to be applied most accurately the daily refinery samples should be taken in the same way, with three repeats taken at 20 minute intervals. The operators should then use the mean values to select the appropriate correlation and manipulate the furnace temperature or D4 temperature according to:

* the regression coefficient in the correlation and,
* the desired change in surface area.

It is also advisable that future projects should follow a similar sampling technique with a view to reducing the impact of short-term variability.

# 6 Recommendations

### for future control of sga surface area

1. The sampling regime of three repeat samples with 20 minute intervals should be used for the daily refinery sample.
2. The regression coefficient in the correlations developed and the graphs of the regression models should be used in conjunction with the daily refinery sample to control SGA surface area.
3. Either furnace temperature or D4 temperature could be utilised to control surface area for units 5, 6 & 8. The choice should be made based on which temperature is currently the most stable, and whether there are any restrictions (such as furnace temperature limits or costs) to adjusting either temperature. However only one temperature should be manipulated at a time to achieve the desired change in surface area.
4. Due to the difficulty in adjusting furnace temperature without affecting D4 temperature in unit 7 the D4 temperature should be used to control surface area and the furnace temperature should remain fixed. However, in the event where furnace temperature is used to control surface area for unit 7 the D4 temperature should be left to vary by itself.
5. The daily refinery samples should be continually monitored and compared with predicted values obtained using the regression coefficients in the correlations to ensure their validity

### for future investigation of Sga surface area

1. Further evidence of the applicability of the correlations over a wider range of unit conditions should be found by conducting similar sample runs done in this project but at other, more extreme, temperature constants. This will also confirm whether the effect of furnace temperature or D4 temperature on SGA surface area can be considered independent of the other temperature for a wide range of unit conditions.
2. An investigation of the effect of gas flow rate is desirable and should be conducted by designing an experiment that incorporates the direct manipulation of gas flow rate. However it is of a lower priority since the correlations developed in this project apply for most commonly encountered gas flow rates.

# Appendices

## Appendix A: Sampling Schedule and Results

**Table A.1** Unit 5 Results

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Sample ID | *T*D4 [oC] | *T*f [oC] | *G* [SCM/h] | *SA* [m2/g] | Order |
| *Variation of Furnace Temperature - Run #1* | | | | | |
| U5-735-930-A | 736 | 931 | 4189 | 82.5 |  |
| U5-735-930-B | 735 | 931 | 4189 | 81.4 |  |
| U5-735-930-C | 737 | 932 | 4178 | 83.6 |  |
| **U5-735-930-Mean** | 736 | **931** | **4185** | **82.5** | **4** |
| U5-735-940-A | 735 | 940 | 4287 | 77.9 |  |
| U5-735-940-B | 735 | 940 | 4285 | 79.8 |  |
| U5-735-940-C | 735 | 941 | 4288 | 79.8 |  |
| **U5-735-940-Mean** | **735** | **940** | **4287** | **79.2** | **3** |
| U5-735-950-A | 733 | 950 | 4289 | 78.1 |  |
| U5-735-950-B | 734 | 950 | 4288 | 78.4 |  |
| U5-735-950-C | 735 | 951 | 4289 | 78.3 |  |
| **U5-735-950-Mean** | **734** | **950** | **4289** | **78.2** | **2** |
| U5-735-960-A | 728 | 960 | 4290 | 77.9 |  |
| U5-735-960-B | 734 | 959 | 4288 | 75.1 |  |
| U5-735-960-C | 736 | 959 | 4283 | 79.0 |  |
| **U5-735-960-Mean** | **732** | **959** | **4287** | **77.3** | **1** |
| U5-735-970-A | 735 | 970 | 4288 | 77.4 |  |
| U5-735-970-B | 734 | 971 | 4288 | 76.7 |  |
| U5-735-970-C | 732 | 972 | 4289 | 77.5 |  |
| **U5-735-970-Mean** | **734** | **971** | **4288** | **77.2** | **6** |
| U5-735-980-A | 736 | 981 | 4288 | 77.6 |  |
| U5-735-980-B | 735 | 979 | 4288 | 80.2 |  |
| U5-735-980-C | 734 | 979 | 4286 | 76.7 |  |
| **U5-735-980-Mean** | **735** | **979** | **4287** | **78.2** | **5** |
| *Variation of Furnace Temperature - Run #2* | | | | | |
| U5-710-930-A | 711 | 931 | 3330 | 87.0 |  |
| U5-710-930-B | 709 | 931 | 3367 | 84.3 |  |
| U5-710-930-C | 709 | 929 | 3385 | 82.9 |  |
| **U5-710-930-Mean** | **710** | **930** | **3361** | **84.8** | **16** |
| U5-710-945-A | 711 | 947 | 3674 | 81.2 |  |
| U5-710-945-B | 710 | 948 | 3561 | 78.3 |  |
| U5-710-945-C | 709 | 947 | 3465 | 78.9 |  |
| **U5-710-945-Mean** | **710** | **947** | **3567** | **79.5** | **12** |
| U5-710-970-A | 710 | 970 | 3384 | 78.0 |  |
| U5-710-970-B | 710 | 969 | 3382 | 76.3 |  |
| U5-710-970-C | 711 | 970 | 3382 | 78.7 |  |
| **U5-710-970-Mean** | **710** | **970** | **3383** | **77.7** | **13** |
| U5-710-985-A | 707 | 985 | 3380 | 76.0 |  |
| U5-710-985-B | 707 | 986 | 3379 | 75.8 |  |
| U5-710-985-C | 705 | 985 | 3380 | 73.3 |  |
| **U5-710-985-Mean** | **706** | **985** | **3380** | **75.1** | **15** |
| U5-710-1000-A | 711 | 1000 | 3385 | 71.7 |  |
| U5-710-1000-B | 711 | 1000 | 3386 | 69.5 |  |
| U5-710-1000-C | 710 | 1001 | 3385 | 72.1 |  |
| **U5-710-1000-Mean** | **711** | **1000** | **3385** | **71.1** | **14** |
| *Variation of D4 Temperature - Run #1* | | | | | |
| U5-700-960-A | 700 | 960 | 4293 | 84.5 |  |
| U5-700-960-B | 699 | 960 | 4292 | 84.0 |  |
| U5-700-960-C | 700 | 960 | 4292 | 88.8 |  |
| **U5-700-960-Mean** | **700** | **960** | **4292** | **85.8** | **9** |
| U5-710-960-A | 710 | 960 | 4290 | 80.5 |  |
| U5-710-960-B | 710 | 959 | 4290 | 82.1 |  |
| U5-710-960-C | 710 | 960 | 4290 | 80.7 |  |
| **U5-710-960-Mean** | **710** | **960** | **4290** | **81.1** | **8** |
| U5-720-960-A | 722 | 960 | 4285 | 82.1 |  |
| U5-720-960-B | 721 | 959 | 4285 | 78.1 |  |
| U5-720-960-C | 720 | 960 | 4285 | 79.7 |  |
| **U5-720-960-Mean** | **721** | **960** | **4285** | **80.0** | **7** |
| U5-750-960-A | 749 | 960 | 4289 | 81.8 |  |
| U5-750-960-B | 749 | 961 | 4288 | 78.9 |  |
| U5-750-960-C | 751 | 960 | 4288 | 77.6 |  |
| **U5-750-960-Mean** | **750** | **960** | **4288** | **79.5** | **10** |
| U5-760-960-A | 759 | 960 | 4290 | 79.1 |  |
| U5-760-960-B | 758 | 960 | 4291 | 77.3 |  |
| U5-760-960-C | 759 | 960 | 4290 | 74.9 |  |
| **U5-760-960-Mean** | **759** | **960** | **4290** | **77.1** | **11** |
| *Variation of D4 Temperature - Run #2* | | | | | |
| U5-710-940-A | 709 | 938 | 4284 | 76.9 |  |
| U5-710-940-B | 709 | 942 | 4281 | 77.0 |  |
| U5-710-940-C | 712 | 940 | 4279 | 75.8 |  |
| **U5-710-940-Mean** | **710** | **940** | **4281** | **76.5** | **17** |
| U5-750-940-A | 749 | 938 | 4279 | 75.3 |  |
| U5-750-940-B | 752 | 939 | 4278 | 77.3 |  |
| U5-750-940-C | 751 | 941 | 4278 | 79.6 |  |
| **U5-750-940-Mean** | **751** | **939** | **4278** | **77.4** | **18** |
| U5-770-940-A | 768 | 939 | 4277 | 74.4 |  |
| U5-770-940-B | 772 | 936 | 4184 | 76.2 |  |
| U5-770-940-C | 774 | 936 | 4153 | 74.3 |  |
| **U5-770-940-Mean** | **771** | **937** | **4204** | **75.0** | **19** |
| *Long Term Fixed Temperature Trial* | | | | | |
| U5-LT-A | 735 | 961 | 4294 | 77.4 | 1 |
| U5-LT-AA\* | 735 | 961 | 4293 | 78.3 | 2 |
| U5-LT-B | 737 | 956 | 4293 | 87.6 | 3 |
| U5-LT-C | 735 | 964 | 4291 | 80.8 | 4 |
| U5-LT-D | 734 | 959 | 4294 | 70.2 | 5 |
| U5-LT-DA\* | 734 | 960 | 4287 | 74.2 | 6 |
| U5-LT-DB\* | 734 | 960 | 4288 | 73.1 | 7 |
| U5-LT-DC\* | 734 | 959 | 4290 | 77.6 | 8 |
| U5-LT-E | 735 | 959 | 4288 | 72.1 | 9 |
| U5-LT-F | 736 | 960 | 4288 | 70.7 | 10 |
| U5-LT-G | 736 | 960 | 4291 | 70.7 | 11 |
| U5-LT-GA\* | 736 | 960 | 4289 | 76.5 | 12 |
| U5-LT-H | 735 | 960 | 4292 | 71.9 | 13 |
| U5-LT-I | 736 | 960 | 4288 | 71.9 | 14 |
| U5-LT-J | 735 | 959 | 4290 | 72.9 | 15 |
| U5-LT-JA\* | 736 | 960 | 3990 | 79.9 | 16 |
| U5-LT-K | 734 | 962 | 3881 | 75.4 | 17 |
| U5-LT-KA\* | 734 | 960 | 3187 | 82.7 | 18 |
| U5-LT-KB\* | 735 | 959 | 4285 | 77.7 | 19 |
| U5-LT-KC\* | 735 | 960 | 4288 | 75.9 | 20 |
| U5-LT-L | 733 | 961 | 4286 | 75.3 | 21 |
| U5-LT-M | 736 | 960 | 4287 | 72.4 | 22 |
| U5-LT-N | 739 | 970 | 4017 | 72.8 | 23 |

**\***Daily Refinery Samples Note: The sample ID is in the format: Unit# – Nominal *T*D4 – Nominal *T*f

**Figure A.1** Unit 5 Sampling Runs – Nominal Temperatures

**Table A.2** Unit 6 Results

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Sample ID | *T*D4 [oC] | *T*f [oC] | *G* [SCM/h] | *SA* [m2/g] | Order |
| *Variation of Furnace Temperature - Run #1* | | | | | |
| U6-720-930-A | 720 | 930 | 4189 | 76.6 |  |
| U6-720-930-B | 720 | 929 | 4189 | 76.9 |  |
| U6-720-930-C | 720 | 929 | 4176 | 77.1 |  |
| **U6-720-930-Mean** | **720** | **929** | **4185** | **76.8** | **3** |
| U6-720-940-A | 719 | 933 | 3985 | 76.4 |  |
| U6-720-940-B | 719 | 938 | 3963 | 75.5 |  |
| U6-720-940-C | 718 | 939 | 4023 | 73.8 |  |
| **U6-720-940-Mean** | **719** | **937** | **3990** | **75.2** | **2** |
| U6-720-950-A | 719 | 950 | 4298 | 71.0 |  |
| U6-720-950-B | 721 | 949 | 4299 | 73.8 |  |
| U6-720-950-C | 721 | 950 | 4299 | 74.2 |  |
| **U6-720-950-Mean** | **720** | **949** | **4298** | **73.0** | **1** |
| U6-720-960-A | 721 | 963 | 4107 | 71.4 |  |
| U6-720-960-B | 722 | 962 | 4132 | 70.4 |  |
| U6-720-960-C | 723 | 961 | 4141 | 73.8 |  |
| **U6-720-960-Mean** | **722** | **962** | **4127** | **71.9** | **4** |
| U6-720-970-A | 724 | 969 | 3946 | 77.9 |  |
| U6-720-970-B | 724 | 969 | 3925 | 76.1 |  |
| U6-720-970-C | 727 | 970 | 3916 | 74.6 |  |
| **U6-720-970-Mean** | **725** | **969** | **3929** | **76.2** | **5** |
| U6-720-980-A | 730 | 980 | 4249 | 72.8 |  |
| U6-720-980-B | 733 | 979 | 4248 | 72.2 |  |
| U6-720-980-C | 735 | 980 | 4247 | 75.0 |  |
| **U6-720-980-Mean** | **733** | **980** | **4248** | **73.3** | **6** |
| *Variation of Furnace Temperature - Run #2* | | | | | |
| U6-750-940-A | 750 | 938 | 3980 | 75.3 |  |
| U6-750-940-B | 749 | 939 | 3958 | 77.3 |  |
| U6-750-940-C | 750 | 940 | 3960 | 76.7 |  |
| **U6-750-940-Mean** | **750** | **939** | **3966** | **76.5** | **16** |
| U6-750-950-A | 748 | 950 | 4198 | 74.2 |  |
| U6-750-950-B | 746 | 950 | 4197 | 74.0 |  |
| U6-750-950-C | 747 | 950 | 4196 | 71.7 |  |
| **U6-750-950-Mean** | **747** | **950** | **4197** | **73.3** | **13** |
| U6-750-960-A | 751 | 959 | 3797 | 73.5 |  |
| U6-750-960-B | 748 | 959 | 3797 | 72.6 |  |
| U6-750-960-C | 747 | 959 | 3797 | 73.1 |  |
| **U6-750-960-Mean** | **749** | **959** | **3797** | **73.1** | **12** |
| U6-750-970-A | 750 | 968 | 3599 | 73.5 |  |
| U6-750-970-B | 751 | 969 | 3593 | 72.7 |  |
| U6-750-970-C | 750 | 968 | 3572 | 70.8 |  |
| **U6-750-970-Mean** | **750** | **968** | **3588** | **72.3** | **15** |
| U6-750-990-A | 755 | 990 | 4186 | 68.0 |  |
| U6-750-990-B | 764 | 990 | 4161 | 67.1 |  |
| U6-750-990-C | 771 | 989 | 4117 | 68.0 |  |
| **U6-750-990-Mean** | **763** | **990** | **4155** | **67.7** | **14** |
| *Variation of D4 Temperature - Run #1* | | | | | |
| U6-740-980-A | 741 | 980 | 4201 | 74.6 |  |
| U6-740-980-B | 740 | 980 | 4196 | 74.4 |  |
| U6-740-980-C | 742 | 980 | 4196 | 73.5 |  |
| **U6-740-980-Mean** | **741** | **980** | **4198** | **74.1** | **7** |
| U6-750-980-A | 745 | 980 | 4196 | 72.5 |  |
| U6-750-980-B | 745 | 980 | 4196 | 69.0 |  |
| U6-750-980-C | 746 | 979 | 4195 | 73.0 |  |
| **U6-750-980-Mean** | **745** | **980** | **4196** | **71.5** | **8** |
| U6-760-980-A | 760 | 979 | 3994 | 72.7 |  |
| U6-760-980-B | 755 | 979 | 3984 | 75.0 |  |
| U6-760-980-C | 751 | 980 | 3986 | 72.2 |  |
| **U6-760-980-Mean** | **755** | **979** | **3988** | **73.3** | **9** |
| U6-760-980-D | 759 | 980 | 4197 | 71.2 |  |
| U6-760-980-E | 757 | 980 | 4197 | 72.9 |  |
| U6-760-980-F | 756 | 980 | 4197 | 71.3 |  |
| **U6-760-980-Mean** | **757** | **980** | **4197** | **71.8** | **10** |
| U6-765-980-A | 765 | 978 | 4153 | 71.7 |  |
| U6-765-980-B | 762 | 970 | 3900 | 74.3 |  |
| U6-765-980-C | 754 | 964 | 3518 | 74.9 |  |
| **U6-765-980-Mean** | **760** | **971** | **3857** | **73.6** | **11** |
| *Variation of D4 Temperature - Run #2* | | | | | |
| U6-700-940-A | 704 | 940 | 4191 | 83.0 |  |
| U6-700-940-B | 705 | 940 | 4188 | 80.7 |  |
| U6-700-940-C | 707 | 938 | 4151 | 79.1 |  |
| **U6-700-940-Mean** | **705** | **939** | **4176** | **80.9** | **18** |
| U6-720-940-D | 721 | 940 | 4105 | 80.4 |  |
| U6-720-940-E | 720 | 940 | 4092 | 79.6 |  |
| U6-720-940-F | 720 | 940 | 4985 | 78.3 |  |
| **U6-720-940-Mean** | **720** | **940** | **4394** | **79.4** | **17** |
| U6-730-940-A | 730 | 940 | 4198 | 78.5 |  |
| U6-730-940-B | 730 | 940 | 4198 | 78.3 |  |
| U6-730-940-C | 729 | 940 | 4198 | 79.7 |  |
| **U6-730-940-Mean** | **729** | **940** | **4198** | **78.8** | **20** |
| U6-740-940-A | 739 | 940 | 4197 | 77.2 |  |
| U6-740-940-B | 740 | 940 | 4197 | 77.7 |  |
| U6-740-940-C | 742 | 940 | 4197 | 77.7 |  |
| **U6-740-940-Mean** | **740** | **940** | **4197** | **77.6** | **19** |
| *Long Term Fixed Temperature Trial* | | | | | |
| U6-LT-A\* | 736 | 960 | 4196 | 74.2 | 1 |
| U6-LT-A | 739 | 959 | 4198 | 76.5 | 2 |
| U6-LT-B | 734 | 960 | 4226 | 74.9 | 3 |
| U6-LT-C | 747 | 960 | 4246 | 74.6 | 4 |
| U6-LT-C\* | 760 | 960 | 4247 | 73.4 | 5 |
| U6-LT-D | 743 | 960 | 4224 | 67.5 | 6 |
| U6-LT-D\* | 736 | 960 | 4193 | 74.0 | 7 |
| U6-LT-E | 736 | 960 | 4061 | 69.8 | 8 |
| U6-LT-F | 735 | 961 | 4196 | 69.9 | 9 |
| U6-LT-G | 735 | 960 | 4197 | 71.2 | 10 |
| U6-LT-GA\* | 736 | 961 | 4195 | 75.8 | 11 |
| U6-LT-GB\* | 750 | 925 | 3792 | 70.3 | 12 |
| U6-LT-GC\* | 738 | 960 | 4196 | 74.1 | 13 |

\*Daily Refinery Samples Note: The sample ID is in the format: Unit# – Nominal *T*D4 – Nominal *T*f

**Figure A.2** Unit 6 Sampling Runs – Nominal Temperatures

**Table A.3** Unit 7 Results

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Sample ID | *T*D4 [oC] | *T*f [oC] | *G* [SCM/h] | *SA* [m2/g] | Order |
| *Variation of Furnace Temperature - Run #1* | | | | | |
| U7-800-1050-A | 803 | 1043 | 4180 | 93.4 |  |
| U7-800-1050-B | 797 | 1041 | 4099 | 95.5 |  |
| U7-800-1050-C | 798 | 1048 | 3964 | 87.5 |  |
| **U7-800-1050-Mean** | **799** | **1044** | **4081** | **92.2** | **1** |
| U7-800-1060-A | 828 | 1055 | 3942 | 86.3 |  |
| U7-800-1060-B | 828 | 1059 | 3861 | 83.6 |  |
| U7-800-1060-C | 829 | 1061 | 3861 | 81.6 |  |
| **U7-800-1060-Mean** | **828** | **1058** | **3888** | **83.8** | **2** |
| U7-800-1070-A | 831 | 1069 | 3989 | 81.7 |  |
| U7-800-1070-B | 834 | 1068 | 3991 | 81.7 |  |
| U7-800-1070-C | 836 | 1068 | 3990 | 82.7 |  |
| **U7-800-1070-Mean** | **833** | **1068** | **3990** | **82.1** | **3** |
| U7-800-1080-A | 845 | 1081 | 3924 | 78.3 |  |
| U7-800-1080-B | 845 | 1081 | 3979 | 77.3 |  |
| U7-800-1080-C | 843 | 1080 | 3985 | 79.2 |  |
| **U7-800-1080-Mean** | **844** | **1081** | **3963** | **78.3** | **4** |
| U7-800-1090-A | 864 | 1089 | 3849 | 73.5 |  |
| U7-800-1090-B | 865 | 1090 | 3841 | 71.8 |  |
| U7-800-1090-C | 865 | 1091 | 3841 | 72.1 |  |
| **U7-800-1090-Mean** | **865** | **1090** | **3844** | **72.5** | **5** |
| U7-800-1100-A | 869 | 1101 | 3880 | 72.1 |  |
| U7-800-1100-B | 868 | 1101 | 3864 | 71.9 |  |
| U7-800-1100-C | 869 | 1101 | 3845 | 69.2 |  |
| **U7-800-1100-Mean** | **868** | **1101** | **3863** | **71.1** | **6** |
| *Variation of Furnace Temperature - Run #2* | | | | | |
| U7-875-1060-A | 873 | 1059 | 3779 | 74.8 |  |
| U7-875-1060-B | 874 | 1059 | 3772 | 69.7 |  |
| U7-875-1060-C | 874 | 1060 | 3754 | 71.7 |  |
| **U7-875-1060-Mean** | **874** | **1059** | **3768** | **72.1** | **12** |
| U7-885-1070-A | 885 | 1069 | 3781 | 68.3 |  |
| U7-885-1070-B | 885 | 1069 | 3753 | 69.1 |  |
| U7-885-1070-C | 885 | 1069 | 3695 | 66.9 |  |
| **U7-885-1070-Mean** | **885** | **1069** | **3743** | **68.1** | **14** |
| U7-820-1080-A | 818 | 1080 | 3984 | 85.0 |  |
| U7-820-1080-B | 818 | 1080 | 3984 | 83.8 |  |
| U7-820-1080-C | 817 | 1081 | 3838 | 82.6 |  |
| **U7-820-1080-Mean** | **818** | **1081** | **3935** | **83.8** | **15** |
| U7-870-1090-A | 875 | 1090 | 3989 | 73.3 |  |
| U7-870-1090-B | 875 | 1090 | 3989 | 72.6 |  |
| U7-870-1090-C | 874 | 1089 | 3977 | 71.3 |  |
| **U7-870-1090-Mean** | **875** | **1090** | **3985** | **72.4** | **16** |
| U7-910-1100-A | 903 | 1099 | 3781 | 65.0 |  |
| U7-910-1100-B | 905 | 1099 | 3777 | 64.8 |  |
| U7-910-1100-C | 907 | 1099 | 3777 | 63.4 |  |
| **U7-910-1100-Mean** | **905** | **1099** | **3778** | **64.4** | **13** |
| *Variation of D4 Temperature - Run #1* | | | | | |
| U7-780-1050-A | 775 | 1050 | 3400 | 84.9 |  |
| U7-780-1050-B | 776 | 1051 | 3400 | 83.8 |  |
| U7-780-1050-C | 776 | 1051 | 3400 | 82.7 |  |
| **U7-780-1050-Mean** | **776** | **1051** | **3400** | **83.8** | **9** |
| U7-810-1050-A | 809 | 1050 | 3500 | 87.6 |  |
| U7-810-1050-B | 809 | 1050 | 3500 | 87.5 |  |
| U7-810-1050-C | 808 | 1050 | 3500 | 83.7 |  |
| **U7-810-1050-Mean** | **809** | **1050** | **3500** | **86.3** | **7** |
| U7-820-1050-A | 824 | 1051 | 3700 | 87.1 |  |
| U7-820-1050-B | 825 | 1051 | 3700 | 86.3 |  |
| U7-820-1050-C | 825 | 1050 | 3700 | 84.5 |  |
| **U7-820-1050-Mean** | **824** | **1050** | **3700** | **86.0** | **8** |
| U7-830-1050-A | 830 | 1051 | 4143 | 80.0 |  |
| U7-830-1050-B | 832 | 1049 | 4130 | 82.2 |  |
| U7-830-1050-C | 830 | 1050 | 4126 | 82.3 |  |
| **U7-830-1050-Mean** | **830** | **1050** | **4133** | **81.5** | **10** |
| U7-860-1050-A | 863 | 1050 | 3710 | 71.5 |  |
| U7-860-1050-B | 865 | 1051 | 3717 | 74.8 |  |
| U7-860-1050-C | 868 | 1052 | 3770 | 70.7 |  |
| **U7-860-1050-Mean** | **865** | **1051** | **3732** | **72.3** | **11** |
| *Variation of D4 Temperature - Run #2* | | | | | |
| U7-845-1070-A | 846 | 1070 | 4084 | 78.5 |  |
| U7-845-1070-B | 847 | 1070 | 4084 | 79.4 |  |
| U7-845-1070-C | 848 | 1070 | 4085 | 75.5 |  |
|  | **847** | **1070** | **4084** | **77.8** | **17** |
| U7-860-1070-A | 861 | 1074 | 3989 | 79.1 |  |
| U7-860-1070-B | 843 | 1064 | 3972 | 78.5 |  |
| U7-860-1070-C | 826 | 1070 | 3516 | 79.9 |  |
|  | **843** | **1069** | **3826** | **79.2** | **19** |
| U7-870-1070-A | 871 | 1069 | 3842 | 72.0 |  |
| U7-870-1070-B | 875 | 1071 | 3836 | 73.8 |  |
| U7-870-1070-C | 875 | 1068 | 3770 | 75.7 |  |
|  | **874** | **1069** | **3816** | **73.8** | **18** |

Note: The sample ID is in the format: Unit# – Nominal *T*D4 – Nominal *T*f

**Figure A.3** Unit 7 Sampling Runs – Nominal Temperatures

As explained in the Results chapter, despite attempting to maintain a constant D4 temperature, it did vary according to the furnace temperature.

**Table A.4** Unit 8 Results

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Sample ID | *T*D4 [oC] | *T*f [oC] | *G* [SCM/h] | *SA* [m2/g] | Order |
| *Variation of Furnace Temperature - Run #1* | | | | | |
| U8-685-940-A | 678 | 940 | 4646 | 81.2 |  |
| U8-685-940-B | 678 | 940 | 4645 | 80.8 |  |
| U8-685-940-C | 678 | 940 | 4644 | 84.1 |  |
| **U8-685-940-Mean** | **678** | **940** | **4645** | **82.0** | **5** |
| U8-685-945-A | 684 | 938 | 3420 | 77.3 |  |
| U8-685-945-B | 684 | 941 | 3166 | 71.8 |  |
| U8-685-945-C | 685 | 952 | 3197 | 69.3 |  |
| **U8-685-945-Mean** | **684** | **944** | **3261** | **72.8** | **1** |
| U8-685-960-A | 682 | 957 | 4295 | 72.6 |  |
| U8-685-960-B | 682 | 953 | 4214 | 78.1 |  |
| U8-685-960-C | 682 | 953 | 4112 | 75.7 |  |
| **U8-685-960-Mean** | **682** | **955** | **4207** | **75.5** | **2** |
| U8-685-960-D | 676 | 960 | 4640 | 78.8 |  |
| U8-685-960-E | 675 | 956 | 4601 | 79.3 |  |
| U8-685-960-F | 676 | 957 | 4527 | 78.3 |  |
| **U8-685-960-Mean** | **676** | **958** | **4589** | **78.8** | **6** |
| U8-685-970-A | 677 | 968 | 4523 | 78.9 |  |
| U8-685-970-B | 677 | 968 | 4489 | 77.3 |  |
| U8-685-970-C | 677 | 968 | 4457 | 76.3 |  |
| **U8-685-970-Mean** | **677** | **968** | **4489** | **77.5** | **3** |
| U8-685-980-A | 677 | 980 | 4392 | 75.9 |  |
| U8-685-980-B | 677 | 981 | 4390 | 74.9 |  |
| U8-685-980-C | 677 | 980 | 4391 | 75.1 |  |
| **U8-685-980-Mean** | **677** | **980** | **4391** | **75.3** | **4** |
| *Variation of Furnace Temperature - Run #2* | | | | | |
| U8-645-930-A | 648 | 931 | 3995 | 81.0 |  |
| U8-645-930-B | 648 | 930 | 3995 | 77.8 |  |
| U8-645-930-C | 649 | 931 | 3994 | 77.8 |  |
| **U8-645-930-Mean** | **649** | **930** | **3994** | **78.9** | **13** |
| U8-645-940-A | 648 | 942 | 3976 | 79.2 |  |
| U8-645-940-B | 647 | 939 | 3994 | 78.9 |  |
| U8-645-940-C | 647 | 940 | 3994 | 79.0 |  |
| **U8-645-940-Mean** | **647** | **940** | **3988** | **79.0** | **14** |
| U8-645-950-A | 648 | 948 | 3321 | 80.7 |  |
| U8-645-950-B | 648 | 948 | 3256 | 80.1 |  |
| U8-645-950-C | 648 | 950 | 3200 | 80.2 |  |
| **U8-645-950-Mean** | **648** | **949** | **3259** | **80.3** | **16** |
| U8-645-960-A | 644 | 965 | 3735 | 76.6 |  |
| U8-645-960-B | 644 | 970 | 3970 | 75.9 |  |
| U8-645-960-C | 644 | 963 | 4096 | 77.3 |  |
| **U8-645-960-Mean** | **644** | **966** | **3934** | **76.6** | **12** |
| U8-645-960-D | 651 | 960 | 4296 | 77.7 |  |
| U8-645-960-E | 651 | 960 | 4296 | 78.5 |  |
| U8-645-960-F | 651 | 959 | 4279 | 77.7 |  |
| **U8-645-960-Mean** | **651** | **960** | **4290** | **78.0** | **18** |
| U8-645-970-A | 641 | 970 | 3983 | 75.8 |  |
| U8-645-970-B | 641 | 966 | 3902 | 75.9 |  |
| U8-645-970-C | 642 | 965 | 3701 | 76.2 |  |
| **U8-645-970-Mean** | **641** | **967** | **3862** | **76.0** | **15** |
| U8-645-990-A | 647 | 991 | 4288 | 71.7 |  |
| U8-645-990-B | 647 | 990 | 4288 | 69.7 |  |
| U8-645-990-C | 647 | 990 | 4289 | 69.9 |  |
| **U8-645-990-Mean** | **647** | **990** | **4288** | **70.5** | **17** |
| *Variation of D4 Temperature - Run #1* | | | | | |
| U8-635-940-A | 634 | 940 | 2501 | 82.7 |  |
| U8-635-940-B | 635 | 940 | 2501 | 82.3 |  |
| U8-635-940-C | 637 | 940 | 2501 | 82.6 |  |
| **U8-635-940-Mean** | **635** | **940** | **2501** | **82.5** | **11** |
| U8-655-940-A | 659 | 940 | 3795 | 78.5 |  |
| U8-655-940-B | 660 | 940 | 3797 | 79.5 |  |
| U8-655-940-C | 660 | 940 | 3795 | 76.4 |  |
| **U8-655-940-Mean** | **660** | **940** | **3796** | **78.1** | **10** |
| U8-665-940-A | 668 | 940 | 3644 | 81.2 |  |
| U8-665-940-B | 668 | 940 | 3710 | 81.1 |  |
| U8-665-940-C | 667 | 942 | 3806 | 82.2 |  |
| **U8-665-940-Mean** | **667** | **940** | **3720** | **81.5** | **7** |
| U8-675-940-A | 676 | 940 | 3768 | 79.1 |  |
| U8-675-940-B | 677 | 940 | 3760 | 77.9 |  |
| U8-675-940-C | 677 | 940 | 3745 | 78.6 |  |
| **U8-675-940-Mean** | **677** | **940** | **3758** | **78.5** | **9** |
| U8-695-940-A | 697 | 942 | 4306 | 79.4 |  |
| U8-695-940-B | 697 | 941 | 4342 | 79.4 |  |
| U8-695-940-C | 697 | 940 | 4287 | 74.5 |  |
| **U8-695-940-Mean** | **697** | **941** | **4312** | **77.8** | **8** |
| *Variation of D4 Temperature - Run #2* | | | | | |
| U8-630-950-A | 629 | 951 | 4163 | 78.1 |  |
| U8-630-950-B | 628 | 950 | 4173 | 79.9 |  |
| U8-630-950-C | 628 | 950 | 4177 | 78.7 |  |
| **U8-630-950-Mean** | **628** | **950** | **4171** | **78.9** | **19** |
| U8-650-950-A | 647 | 948 | 4017 | 75.1 |  |
| U8-650-950-B | 647 | 949 | 3987 | 74.7 |  |
| U8-650-950-C | 648 | 949 | 3965 | 77.0 |  |
| **U8-650-950-Mean** | **647** | **949** | **3990** | **75.6** | **20** |
| U8-660-950-A | 664 | 948 | 4168 | 75.8 |  |
| U8-660-950-B | 665 | 947 | 4074 | 73.2 |  |
| U8-660-950-C | 666 | 950 | 4036 | 72.9 |  |
| **U8-660-950-Mean** | **665** | **949** | **4093** | **74.0** | **21** |
| U8-680-950-A | 680 | 951 | 4152 | 74.3 |  |
| U8-680-950-B | 679 | 950 | 4184 | 71.7 |  |
| U8-680-950-C | 679 | 949 | 4185 | 70.9 |  |
| **U8-680-950-Mean** | **679** | **950** | **4174** | **72.3** | **23** |
| U8-695-950-A | 699 | 952 | 4210 | 70.2 |  |
| U8-695-950-B | 698 | 953 | 4282 | 67.0 |  |
| U8-695-950-C | 697 | 948 | 4320 | 67.0 |  |
| **U8-695-950-Mean** | **698** | **951** | **4271** | **68.1** | **22** |

Note: The sample ID is in the format: Unit# – Nominal *T*D4 – Nominal *T*f

**Figure A.4** Unit 8 Sampling Runs – Nominal Temperatures

## Appendix B: Detailed Statistical Analysis Procedure

### Example: Unit 5 variation of furnace temperature

**Table B.1** Selected results for Unit 5

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| *Variation of Furnace Temperature - Run #2* | | | | | |
| Sample ID | *T*D4 [oC] | *T*f [oC] | *G* [SCM/h] | *SA* [m2/g] | Observation |
| **U5-710-930-Mean** | **710** | **930** | **3361** | **84.8** | **16** |
| **U5-710-945-Mean** | **710** | **947** | **3567** | **79.5** | **12** |
| **U5-710-960-Mean** | **710** | **960** | **4290** | **81.1** | **8** |
| **U5-710-970-Mean** | **710** | **970** | **3383** | **77.7** | **13** |
| **U5-710-985-Mean** | **706** | **985** | **3380** | **75.1** | **15** |
| **U5-710-1000-Mean** | **711** | **1000** | **3385** | **71.1** | **14** |

1. The sample data was first examined to ensure that the D4 temperature and gas flow rate were held constant. The scatterplot graph tool in Minitab was a useful aid for this step of the analysis.

The tolerance allowed for D4 temperature deviation is ± 5 oC. For this sample run the nominal value chosen was 710 oC and all 6 samples satisfy this criteria.

Since gas flow rate was left uncontrolled there was no nomimal value chosen. Instead a mean value for the gas flow rates for each sample was calculated and a tolerance of ± 10% was allowed. For this sample run, the mean gas flow rate for the 6 samples is 3561 SCM/h. Sample U5-710-960 was taken at a gas flow rate furthest outside the tolerance of ± 10% and hence this sample point is removed. The new mean gas flow rate for the remaining 5 samples is 3415 SCM/h. All the remaining samples were taken at gas flow rates within the allowed tolerance.

1. A regression analysis using the regression tool in Minitab is then conducted on these 5 samples, once using the raw data which consists of all three repeat samples taken at each configuration (see **Table A.1**) and once using only the calculated mean data (see above **Table B.1**).

**Figure B.1** Regression Analysis for Unit 5 Variation of Furnace Temperature

***Mean Data***

|  |  |
| --- | --- |
| Regression Equation:  *SA* = 249 – 0.177 *T*f | |
| S | 1.181 |
| R2 (adj) | 94.6% |
| SE of constant | 20.25 |
| SE of coefficient | 0.021 |

***Raw Data***

|  |  |
| --- | --- |
| Regression Equation:  *SA* = 248 – 0.176 *T*f | |
| S | 1.749 |
| R2 (adj) | 87.2% |
| SE of constant | 17.31 |
| SE of coefficient | 0.018 |



*T*D4 = 710 oC, *G* ≈ 3400 SCM/h

1. The residual graphs are plotted through the regression tool in Minitab and a final check of these graphs confirms that the linear regression assumptions are met:

* Residuals have a mean of 0
* Predictor variables are uncorrelated with the residuals and between each other
* Residuals are not correlated with each other
* Residuals are normally distributed (sample size too small in this case to confirm but the residuals from the raw data regression appear to be normally distributed)

Thus we can be confident with the validity of the regression analysis. The very high adjusted R2 value of 94.6% means that 94.6% of the variability in surface area can be explained by the furnace temperature and demonstrates that there is indeed a very strong correlation between the two.

**Figure B.2** Residual Plots for Regression Analysis on Unit 5 Variation of Furnace Temperature



Had sample U5-710-960 been included in the regression analysis an adjusted R2 value of 90.5% would have been obtained. Although this is still a very good correlation from a statistical point of view, it does indicate that the differing gas flow rate has had an impact on the surface area.

## Appendix C: Regression Coefficient Intervals

**Figure C.1** Regression coefficient intervals (2 standard deviations) for the regression equations found for units 5, 6 & 8



1. At Kwinana refinery holding vessel level is uncontrollable except on Unit 4. All other Units operate at a relatively constant holding vessel level due to the incorporation of a weir type discharge in the holding vessel design. Since Unit 4 was unavailable for sampling, holding vessel level was not investigated in this project. [↑](#footnote-ref-1)
2. With the exception of unit 3 due to ongoing α-phase issues with the SGA product and unit 4 which predominantly produces special products instead of SGA product. [↑](#footnote-ref-2)
3. Units 5 & 6 were chosen because these two calciners are relatively similar in the hope that the results would be comparable. [↑](#footnote-ref-3)
4. A period of 1 hour was used for gas flow rate calculations where the flow rate underwent an increase or decrease during the sampling period to allow for more accurate representation of the calcining conditions. Where gas was held at a stable flow rate the usual 2 hour period was used. [↑](#footnote-ref-4)
5. See **figures 4.2**, **4.3**; and results for unit 8 and unit 7. [↑](#footnote-ref-5)
6. See **Appendix C** for a full figure showing intervals for the correlations for units 5, 6 & 8. [↑](#footnote-ref-6)
7. See the **Executive Summary** for a table of these correlations. [↑](#footnote-ref-7)
8. See **Appendix A** for the operating conditions sampled at. Gas flow rate was above 80% of its maximum. [↑](#footnote-ref-8)
9. See the results of the ‘Long Term’ Fixed Temperature trials. [↑](#footnote-ref-9)