

# **University of Wales Trinity St David**

## **School of Engineering**



# **An Investigation into 4 Stroke SI Gasoline Engine Efficiency**

## **Major Project**

### **M6X00417**

#### **Abstract**

An investigation into the efficiency of a 1 Litre Ford Fox Turbocharged engine using Microsoft Excel and engine cylinder pressure data. Includes the evaluation of combustion thermochemistry, actual cycle efficiency, ideal Otto cycle efficiency, mass fraction burnt and flame speeds.

**Phillip Bristow P144394**

**Advanced Engine Design**

**24/03/2018**

## Acknowledgements

I would like to thank my mentor Malcolm McDonald, who always has been ready to help with access to his extensive knowledge and insights into the project. He has been a constant source of advice and guidance throughout the project and has opened my mind to a different way of thinking, for this he has my gratitude. I would also like to extend my gratitude to my family and friends, who have stood by me for the duration of my studies and provided me with encouragement and support when I have needed it most.

## Declaration of Authenticity

This thesis is the result of the author's original research. It has been composed by the author and has not been previously submitted for examination which has led to the award of a degree

Signed:

Date:

# Contents

|                                                                  |    |
|------------------------------------------------------------------|----|
| Acknowledgements.....                                            | 2  |
| Declaration of Authenticity.....                                 | 2  |
| Contents.....                                                    | 3  |
| Table of Figures.....                                            | 6  |
| Table of Tables.....                                             | 7  |
| Table of Equations.....                                          | 10 |
| Commonly used Symbols and Abbreviations and Constants.....       | 12 |
| Symbols.....                                                     | 12 |
| Abbreviations.....                                               | 13 |
| Introduction.....                                                | 14 |
| Literature Review.....                                           | 15 |
| 1    Combustion Thermochemistry.....                             | 17 |
| 1.1    Air:Fuel Ratio.....                                       | 17 |
| 1.2    Lambda $\lambda$ .....                                    | 19 |
| 1.3    Fuel Equivalence Ratio $\phi$ .....                       | 20 |
| 1.4    Air:Fuel Mass.....                                        | 21 |
| 1.5    Reactants and Products.....                               | 23 |
| 1.6    Molecular Weights of the Burned and Unburned Mixture..... | 29 |
| 1.7    Gas Constant of Air:Fuel Mix.....                         | 31 |
| 1.8    Enthalpy of Formation.....                                | 32 |
| 1.9    Calorific Value.....                                      | 35 |
| 1.10    Ideal Gas Law.....                                       | 36 |
| 2    Pressure Volume Data.....                                   | 37 |
| 2.1    Pressure-Volume Diagrams.....                             | 37 |
| 2.2    Work Done.....                                            | 39 |

|       |                                                      |    |
|-------|------------------------------------------------------|----|
| 2.3   | Cylinder Temperature .....                           | 41 |
| 2.4   | Laminar Flame Speed.....                             | 43 |
| 2.5   | Burn Duration.....                                   | 44 |
| 2.5.1 | Log P Log V .....                                    | 44 |
| 2.5.2 | Polytrophic Index .....                              | 45 |
| 2.5.3 | Extra Pressure from Combustion ( $\Delta P$ ) .....  | 46 |
| 2.5.4 | Mass Fraction Burn .....                             | 47 |
| 2.5.5 | Burn Duration.....                                   | 48 |
| 2.6   | Turbulent Flame Speed .....                          | 49 |
| 3     | Efficiency Calculations using MEP data.....          | 52 |
| 3.1   | MEP .....                                            | 52 |
| 3.2   | BMEP .....                                           | 52 |
| 3.3   | IMEP .....                                           | 53 |
| 3.4   | FMEP .....                                           | 55 |
| 3.5   | Mechanical Efficiency.....                           | 56 |
| 3.6   | Specific Fuel Consumption .....                      | 58 |
| 3.7   | Brake Thermal Efficiency.....                        | 59 |
| 3.8   | Indicated Thermal Efficiency.....                    | 60 |
| 3.9   | Exhaust Energy.....                                  | 62 |
| 4     | Otto Cycle Efficiency .....                          | 64 |
| 4.1   | Specific Heats .....                                 | 64 |
| 4.2   | Thermal Otto Cycle Efficiency .....                  | 70 |
| 4.3   | Ideal Otto Cycle.....                                | 73 |
| 4.4   | Ideal Otto Cycle with variable CV and $\gamma$ ..... | 75 |
| 4.5   | Ideal Otto Cycle with fixed $\gamma$ .....           | 76 |
| 4.6   | Ideal Otto Cycle Temperature Results .....           | 77 |
| 4.7   | Ideal Otto Cycle Pressure Results.....               | 78 |
| 4.8   | Ideal Otto Cycle Efficiency .....                    | 79 |

|     |                                                                         |     |
|-----|-------------------------------------------------------------------------|-----|
| 5   | Conclusion.....                                                         | 82  |
| 6   | Appendix .....                                                          | 86  |
| 6.1 | Engine Specifications .....                                             | 86  |
| 6.2 | Otto Cycle Definition.....                                              | 86  |
| 6.3 | Otto Cycle Thermal Efficiency Derivation .....                          | 87  |
| 6.4 | Thermodynamic Property Tables (Turns, 2006) .....                       | 89  |
| 6.5 | Molecular Thermodynamic Properties (Heywood, 1988), (Turns, 2006) ..... | 90  |
| 6.6 | Ford Engine Test Data .....                                             | 90  |
| 6.7 | Example of Ideal Otto Cycle Calculations.....                           | 92  |
| 6.8 | Example of PV data, Temperature, and Specific Heat calculations .....   | 100 |
| 7   | References .....                                                        | 115 |

## Table of Figures

|                                                                                          |    |
|------------------------------------------------------------------------------------------|----|
| Figure 1: Rich and Lean AFR and Lambda Comparison (X-Engineer, 2018) .....               | 18 |
| Figure 2: Enthalpy of Formation Diagram (Sparknotes, 2018) .....                         | 32 |
| Figure 3: PV Diagram (Nuclear Power, 2018) .....                                         | 37 |
| Figure 4: Comparison of PVs at 1000RPM and 6500RPM at Full Load .....                    | 38 |
| Figure 5: A Comparison of PVs at Full and Part Loads at 1500RPM .....                    | 38 |
| Figure 6: A Comparison of N/A and Turbo PV Data at 1000RPM .....                         | 39 |
| Figure 7: A Comparison of Cylinder Temperatures at 1000RPM and 6500RPM at Full Load..... | 43 |
| Figure 8: 1000RPM Log P vs Log V Diagram.....                                            | 45 |
| Figure 9: Extra Pressure from Combustion at 1000RPM .....                                | 47 |
| Figure 10: MFB at 1000RPM .....                                                          | 48 |
| Figure 11: Flame Speeds .....                                                            | 51 |
| Figure 12: IMEP shown on PV Diagram (Rodgers, 2014) .....                                | 54 |
| Figure 13: Example of Friction of components in engine (X-Engineer, 2018) .....          | 56 |
| Figure 14: Brake Thermal Efficiency .....                                                | 60 |
| Figure 15: Brake Thermal Efficiency vs Indicated Thermal Efficiency - Full Load .....    | 61 |
| Figure 16: Diatomic Molecule Internal Energies (Turns, 2006) .....                       | 65 |
| Figure 17: Cv shown on a graph of Internal Energy vs Temperature (Turns, 2006) .....     | 65 |
| Figure 18: Cp shown on a graph of Enthalpy vs Temperature (Turns, 2006) .....            | 65 |
| Figure 19: Graph and Polynomial to calculate Cp of Oxygen.....                           | 66 |
| Figure 20: Comparison of Oxygen Cp at 6500RPM Full Load.....                             | 69 |
| Figure 21: Ratio of Specific Heat at 6500RPM Full Load .....                             | 69 |
| Figure 22: 4000RPM Ideal Otto Cycle Full Load.....                                       | 74 |
| Figure 23: Comparison of Calculated Efficiencies.....                                    | 83 |
| Figure 24: Comparison between Actual and Ideal Cycles at 4000RPM Full Load.....          | 84 |
| Figure 25: Distribution of Fuel Energy at 4000RPM Full Load .....                        | 85 |
| Figure 26: Distribution of Fuel Energy at 4000RPM Part Load .....                        | 85 |
| Figure 27: Example of Ideal Otto Cycle (Sankararaj, 2018).....                           | 87 |

## Table of Tables

|                                                                              |    |
|------------------------------------------------------------------------------|----|
| Table 1: AFR .....                                                           | 17 |
| Table 2: Lambda Data .....                                                   | 19 |
| Table 3: Fuel Equivalence Ratio .....                                        | 20 |
| Table 4: Fuel Mass (Kg/Cylinder) .....                                       | 21 |
| Table 5: Air Mass (Kg/Cylinder).....                                         | 22 |
| Table 6: Air:Fuel Mass (Kg/Cylinder).....                                    | 22 |
| Table 7: Reactant Quantity - Carbon .....                                    | 24 |
| Table 8: Reactant Quantity - Hydrogen .....                                  | 24 |
| Table 9: Quantity of Product - Carbon Dioxide.....                           | 26 |
| Table 10: Quantity of Product - Carbon Monoxide.....                         | 26 |
| Table 11: Quantity of Product - Water .....                                  | 27 |
| Table 12: Quantity of Product - Oxygen .....                                 | 27 |
| Table 13: Quantity of Product - Nitrogen .....                               | 28 |
| Table 14: Molecular Weight Unburned .....                                    | 29 |
| Table 15: Molecular Weight Burned .....                                      | 30 |
| Table 16: R Burned.....                                                      | 31 |
| Table 17: R Unburned .....                                                   | 31 |
| Table 18: Enthalpy Required .....                                            | 33 |
| Table 19: Enthalpy Released .....                                            | 33 |
| Table 20: Net Enthalpy Released .....                                        | 34 |
| Table 21: Calorific Value .....                                              | 35 |
| Table 22: Extract of Work Done per degree data of Ford Fox at Full Load..... | 40 |
| Table 23: Total Work Done- Full Load.....                                    | 40 |
| Table 24: Total Work Done - Part Load.....                                   | 40 |
| Table 25: Total Work Done - Naturally Aspirated.....                         | 41 |
| Table 26: Extract of Temperature data at 6500RPM Full Load.....              | 42 |
| Table 27: Laminar Flame Speed Parameters (Heywood, 1988).....                | 43 |
| Table 28: Laminar Flame Speed .....                                          | 44 |
| Table 29: Polytropic Index Full Load .....                                   | 46 |
| Table 30: Polytrophic Index Part Load .....                                  | 46 |
| Table 31: Burn Duration at Full Load .....                                   | 49 |
| Table 32: Burn Duration at Part Load .....                                   | 49 |
| Table 33: Flame Speeds - Full Load .....                                     | 50 |

|                                                                                            |    |
|--------------------------------------------------------------------------------------------|----|
| Table 34: Flame Speeds - Part Load .....                                                   | 50 |
| Table 35: BMEP (Bar) .....                                                                 | 53 |
| Table 36: IMEP-Full Load.....                                                              | 54 |
| Table 37: IMEP-Part Load.....                                                              | 54 |
| Table 38: FMEP-Full Load.....                                                              | 55 |
| Table 39: FMEP - Part Load .....                                                           | 55 |
| Table 40: Mechanical Efficiency - Full Load .....                                          | 57 |
| Table 41: Mechanical Efficiency - Part Load .....                                          | 57 |
| Table 42: Specific Fuel Consumption (Kg/kWh).....                                          | 58 |
| Table 43: Brake Thermal Efficiency.....                                                    | 59 |
| Table 44: Indicated Thermal Efficiency - Full Load .....                                   | 61 |
| Table 45: Indicated Thermal Efficiency - Part Load.....                                    | 61 |
| Table 46: Fuel Energy (KJ/S).....                                                          | 62 |
| Table 47: Energy Lost (KJ/s) .....                                                         | 62 |
| Table 48: Percentage Fuel Energy Lost down Exhaust .....                                   | 63 |
| Table 49: Extract of Specific Heat Data at 6500 RPM Full Load using Polynomials.....       | 68 |
| Table 50: Extract of Specific Heat Data at 6500 RPM Full Load using Curve Coefficient..... | 68 |
| Table 51: Full Load Otto Thermal Efficiency using Curve Coefficient method .....           | 71 |
| Table 52: Full Load Otto Thermal Efficiency using Polynomial method .....                  | 71 |
| Table 53: Part Load Otto Cycle Thermal Efficiency using Curve Coefficient method .....     | 72 |
| Table 54: Part Load Otto Thermal Efficiency using Polynomial method .....                  | 72 |
| Table 55: Extract of calculations for T3.....                                              | 75 |
| Table 56: Extract of Variable Cv Calculations for Qout.....                                | 76 |
| Table 57: Full Load Ideal Otto Cycle Temperature Results .....                             | 77 |
| Table 58: Part Load Ideal Otto Cycle Temperature Results .....                             | 77 |
| Table 59: Full Load Ideal Otto Cycle Pressure Results .....                                | 78 |
| Table 60: Part Load Ideal Otto Cycle Pressure Results .....                                | 79 |
| Table 61: Full Load Ideal Otto Cycle Efficiency .....                                      | 81 |
| Table 62: Part Load Ideal Otto Cycle Efficiency .....                                      | 81 |
| Table 63: Summary of Calculated Efficiencies Full Load.....                                | 83 |
| Table 64: Summary of Calculated Efficiencies Part Load .....                               | 83 |
| Table 65: Fuel Energy Distribution Full Load .....                                         | 85 |
| Table 66: Fuel Energy Distribution Part Load .....                                         | 85 |
| Table 67: Ford Fox 1 Litre Engine Specification .....                                      | 86 |

|                                                            |    |
|------------------------------------------------------------|----|
| Table 68: Test Data Air:Fuel Ratio.....                    | 90 |
| Table 69: Test Data Fuel Mass (Kg/h) .....                 | 91 |
| Table 70: Test Data Specific Fuel Consumption (g/kWh)..... | 91 |
| Table 71: Test Data Turbo Out Temperature (Degrees) .....  | 91 |
| Table 72: Test Data Intercooler Air Out (Degrees) .....    | 92 |
| Table 73: Test Data BMEP (kN/m <sup>2</sup> ) .....        | 92 |

## Table of Equations

|                                                                                         |    |
|-----------------------------------------------------------------------------------------|----|
| Equation 1: Air:Fuel Ratio (Heywood, 1988).....                                         | 17 |
| Equation 2: Lambda using AFR (X-Engineer, 2018).....                                    | 19 |
| Equation 3: Lambda using FER (Heywood, 1988) .....                                      | 19 |
| Equation 4: FER using AFR (Turns, 2006) .....                                           | 20 |
| Equation 5: FER using $\lambda$ (Heywood, 1988) .....                                   | 20 |
| Equation 6: Fuel Mass Conversion.....                                                   | 21 |
| Equation 7: Air Mass (Kg/Cylinder) .....                                                | 21 |
| Equation 8:C8H18 Reactant and Product Calculation (Heywood, 1988).....                  | 23 |
| Equation 9: C8H18 Stoichiometric Combustion Reactants and Products (Heywood, 1988)..... | 23 |
| Equation 10: Product & Reactant Calculation when Rich at 3000RPM Full Load.....         | 25 |
| Equation 11: Product & Reactant Calculation when Lean at 1500RPM Full Load .....        | 25 |
| Equation 12:Unburned Molecular Weight.....                                              | 29 |
| Equation 13: Burned Molecular Weight .....                                              | 29 |
| Equation 14: Gas Constant (Heywood, 1988) .....                                         | 31 |
| Equation 15:Enthalpy Required (Heywood, 1988) .....                                     | 32 |
| Equation 16: Enthalpy Released (Heywood, 1988).....                                     | 32 |
| Equation 17:Net Enthalpy Released (Heywood, 1988).....                                  | 32 |
| Equation 18: Higher Calorific Value (Turns, 2006).....                                  | 35 |
| Equation 19: Ideal Gas Law A (Heywood, 1988) .....                                      | 36 |
| Equation 20: Ideal Gas Law B (Heywood, 1988) .....                                      | 36 |
| Equation 21: Work Done per Degree (Heywood, 1988) .....                                 | 39 |
| Equation 22: Net Indicated Work Done (Heywood, 1988) .....                              | 39 |
| Equation 23: Temperature from Ideal Gas Law (Heywood, 1988) .....                       | 41 |
| Equation 24: Laminar Flame Speed (Heywood, 1988).....                                   | 43 |
| Equation 25: Delta P (Heywood, 1988).....                                               | 46 |
| Equation 26: Mass Fraction Burn (Heywood, 1988) .....                                   | 47 |
| Equation 27: Turbulent Flame Velocity (Heywood, 1988).....                              | 49 |
| Equation 28: Mean Effective Pressure (Heywood, 1988) .....                              | 52 |
| Equation 29: BMEP using Torque (Colin R Ferguson, 2001) .....                           | 52 |
| Equation 30: BMEP using Power (Colin R Ferguson, 2001) .....                            | 52 |
| Equation 31: IMEP (Stone, 1992) .....                                                   | 53 |
| Equation 32: FMEP (X-Engineer, 2018).....                                               | 55 |
| Equation 33: Mechanical Efficiency using BMEP (X-Engineer, 2018) .....                  | 56 |

|                                                                                               |    |
|-----------------------------------------------------------------------------------------------|----|
| Equation 34: Mechanical Efficiency using FMEP (X-Engineer, 2018).....                         | 56 |
| Equation 35: SFC from Mass Flow and Power (Heywood, 1988).....                                | 58 |
| Equation 36: Power (Lumley, 1999).....                                                        | 58 |
| Equation 37: SFC using Efficiency and Calorific Value (Lumley, 1999) .....                    | 58 |
| Equation 38: Brake Thermal Efficiency (Heywood, 1988) .....                                   | 59 |
| Equation 39: Indicated Thermal Efficiency (Heywood, 1988).....                                | 60 |
| Equation 40: Specific Heat at constant volume (Heywood, 1988) .....                           | 64 |
| Equation 41: Specific Heat at constant pressure (Heywood, 1988) .....                         | 64 |
| Equation 42: Ratio of Specific Heats (Heywood, 1988) .....                                    | 64 |
| Equation 43: Cp Isooctane (Turns, 2006).....                                                  | 66 |
| Equation 44: Cp Nitrogen and Oxygen (Heywood, 1988).....                                      | 67 |
| Equation 45: Cp Mixture (Heywood, 1988) .....                                                 | 67 |
| Equation 46: Cv Mixture (Heywood, 1988).....                                                  | 67 |
| Equation 47: Thermal Efficiency using Compression Ratio (Heywood, 1988).....                  | 70 |
| Equation 48: Pressure-Volume Relationship (Colin R Ferguson, 2001) .....                      | 73 |
| Equation 49: P2 Calculation (Colin R Ferguson, 2001).....                                     | 73 |
| Equation 50: P3 Calculation (Colin R Ferguson, 2001).....                                     | 73 |
| Equation 51: Temperature-Volume Relationship (Urieli, 2018) .....                             | 73 |
| Equation 52: T2 Calculation (Urieli, 2018) .....                                              | 73 |
| Equation 53: T3 Calculation (Colin R Ferguson, 2001).....                                     | 74 |
| Equation 54: Qin Calculation (Heywood, 1988).....                                             | 74 |
| Equation 55: Cv Conversion (Heywood, 1988) .....                                              | 74 |
| Equation 56: Qout Calculation (Heywood, 1988) .....                                           | 74 |
| Equation 57: dQ Calculation (Heywood, 1988).....                                              | 75 |
| Equation 58: Thermal Efficiency Definition (Nuclear Power, 2018) .....                        | 79 |
| Equation 59: Ideal Otto Cycle Thermal Efficiency (Nuclear Power, 2018).....                   | 79 |
| Equation 60: Heat Supplied to Otto Cycle (Sankararaj, 2018) .....                             | 87 |
| Equation 61: Heat Rejected from Otto Cycle (Sankararaj, 2018) .....                           | 87 |
| Equation 62: Thermal Efficiency of Otto Cycle Definition (Sankararaj, 2018) .....             | 87 |
| Equation 63: Thermal Efficiency of Otto Cycle 1 (Sankararaj, 2018).....                       | 87 |
| Equation 64: Thermal Efficiency of Otto Cycle 2 (Sankararaj, 2018) .....                      | 88 |
| Equation 65: Relationships of Temperature, Volume and Compression Ratio (Heywood, 1988) ..... | 88 |
| Equation 66: Thermal Efficiency using Compression Ratio .....                                 | 88 |

## Commonly used Symbols and Abbreviations and Constants

### Symbols

$C_p$  - Specific Heat at Constant Pressure

$C_v$  – Specific Heat at Constant Volume

$\theta$  – Crank Angle

$^{\circ}$  - Degrees (Angle)

$^{\circ}\text{C}$  – Degrees Celsius

$\Delta$  - Difference

$\phi$  – Fuel Equivalence Ratio

K - Kelvin

$\lambda$  – Lambda

M – Mass

$\mathcal{M}$  - Molecular Mass

$n_r$  – Number of Crank Rotations per power stroke

$\pi$  - Pi

P – Pressure

p - Power

R – Gas Constant

$\tilde{R}$  – Universal Gas Constant

T – Temperature

$\tau$  - Torque

V – Volume

$V_d$  – Cylinder Volume Displaced

## Abbreviations

AFR – Air:Fuel Ratio

ATDC – After Top Dead Centre

BMEP – Brake Mean Effective Pressure

BTDC – Before Top Dead Centre

CA – Crank Angle

cc – Cubic Centimetre

CR – Compression Ratio

ECU – Engine Control Unit

EOC – End of Combustion

FER – Fuel Equivalence Ratio

FMEP – Friction Mean Effective Pressure

HCV – Higher Calorific Value

IMEP – Indicated Mean Effective Pressure

MEP – Mean Effective Pressure

MFB – Mass Fraction Burned

P-V – Pressure - Volume

Qty - Quantity

RPM – Revolutions per Minute

SI – Spark Ignition

SOC – Start of Combustion

TDC – Top Dead Centre

## Introduction

Since the conception of the internal combustion engine in 1867 by Nicolaus Otto, improvement of engine efficiency has always been strived for. The development of engine and fuel technology has resulted in an improvement in thermal efficiency from 11% in 1867 to 25-30% in a typical automotive engine and even 50% in high performance Formula 1 engines. The improvement of engine efficiency is becoming more important, with political pressure being put onto automotive manufacturers to reduce harmful emission and reduce fuel consumption. The efficiency of engines is limited by the laws of thermodynamics. The first law states that the increase in energy of a system is equal to the heat input minus the work done by the system. This means an engine can never be more than 100% efficient. The second law states that it is impossible for a system to completely convert heat into work, there will always be energy lost. From this it can be concluded that engine can never be 100% efficient. There is a theoretical limit to how efficient an engine can be known as the Carnot principle (Nuclear Power, 2018). In summary, it is hard to make an engine have an efficiency much higher than 50%.

This report is an investigation into the various efficiencies of 4-stroke gasoline engines using real engine test data supplied by Ford. It covers the calculations from first principles. The first chapter covers the Combustion Thermochemistry of the engine. Chapter 2 shows how the pressure volume data can be represented in graphical form and used to obtain values for work done and temperature, it also covers the calculations to obtain the flame speeds. Chapter 3 defines mean effective pressure and explains how it can be used to obtain the mechanical, brake and thermal efficiencies of the engine. Chapter 4 considers the calculation of ideal Otto cycle using compression ratio. It also compares the actual thermal efficiency to the ideal Otto efficiency. Chapter 5 provides a conclusion and overall analysis of the study. For ease of reading, only extracts of the calculated data were included in the main text of the study, the complete data can be found in the appendix.

## Literature Review

The investigation into the efficiency of engines and the techniques to improve it have been the subject of intense research and development since the conception of the Internal Combustion Engine. The improvement of efficiency has become a high priority with worldwide attention focusing on the inevitable expiration and environmental impacts of fossil fuels within the next 40 years (Mehrdad Ehsani, 2010). For the fuel supplies to last for as long as possible, it is important that the efficiency of the internal combustion engine is improved.

### **Thermodynamic Analysis of Turbocharged Spark Ignition Engine (Otto Cycle) – Part 1 – Heat Energy available in the Exhaust Gases – M. Mostafavi & B. Agnew**

The authors use thermodynamic principles to calculate the work done, thermal efficiency and energy available in the exhaust gases of a turbocharged spark ignition engine. The efficiency advantages of turbocharged engines over naturally aspirated engines are discussed and the improvements calculated. (M. Mostafavi) The topics covered in this paper are relatable to the study. The methodology used in the calculation of efficiencies and exhaust energy comparable to those that will be used in the investigation.

### **Engine Technologies for Achieving 45% Thermal Efficiency of S.I Engine – K. Nakata, S. Nogawa, D. Takahashi, Y. Yoshihara, A. Kumagai and T. Suzuki**

This paper explains the difference between the thermal efficiencies of theoretical and actual cycles. It also discusses the challenges of engine efficiencies that need to be overcome for improvement and current technology used to improve efficiencies. The paper then goes on to discuss improving efficiency using long stroke design and the various considerations that need to be made in order to make the engine function (K. Nakata, 2015). Although the focus of this paper is on the improvement of efficiency using long stroke design, many of the concepts discussed are relevant to this investigation.

### **A Study on Improvement of Indicated Thermal Efficiency of ICE using High Compression Ratio and Reduction of Cooling Loss – H. Fugimoto, H. Yamamoto, M. Fujimoto and H. Yamashita**

This paper studies the relationship between the improvement of thermal efficiency and compression ratio. It uses thermodynamic principles to obtain theoretical efficiencies. It discusses the effects of the indicated mean effective pressure and the calculation of cooling loss percentages through the use of 1-D model. It also analyses the combustion of the engine. It concludes that there is an ideal compression ratio that gives the best thermal efficiency to cooling loss ratio. The calculations and

theories discussed in this paper are transferrable to the investigation of the Ideal Otto cycle thermal efficiency of this study. (H. Fujimoto, 2011)

**Direct Comparison of an Engine Working under Otto, Miller and Diesel Cycles: Thermodynamic Analysis and Real Engine Performance – Bernardo Ribeiro and Jorge Martins**

This report uses a computer to model the thermal efficiencies of a test engine using the Otto, Miller and Diesel thermodynamic cycles under various load conditions. The specific fuel consumption and BMEP of the cycles are compared and analysed. The effects of variable valve timing and variable compression ratios are also discussed (Martins, 2007). This report explores the effects of part load on the thermal efficiency which will be further investigated in this study.

**Count your Losses – Dr Andy Randolph**

This article discusses the thermal efficiency of 2017 NASCAR cup engines. It explains where efficiency losses are experienced and gives insight as to where efficiency may be improved. It goes on to calculate and discuss the ideal Otto cycle calculated from compression ratio. The Ideal cycle is then overlaid onto measured cylinder pressure data and the differences discussed. The efficiency losses are explained using graphical data (Randolph, 2018). This article is relevant to the study as it details the various losses in efficiency experience by the engine. It also gives real world values to compare to the results of this study.

# 1 Combustion Thermochemistry

In this chapter the combustion thermochemistry used during the study will be explained and analysed. Most of the topics covered in this chapter are used in later chapters to calculate the efficiencies.

## 1.1 Air:Fuel Ratio

The Air:Fuel Ratio is used to define the ratio of air to fuel within the cylinder. The ideal AFR is when there is complete combustion of the fuel within the cylinder and is known as Stoichiometric. If the AFR is higher than stoichiometric it is known as running lean, as there is more air than fuel required for combustion. If the ratio is lower than stoichiometric it the engine is running rich due to the presence of more fuel than is required for perfect combustion. Different fuels have a different stoichiometric AFR depending on their chemical composition (Lambda Power, 2018). Using the data provided it is possible to discover the AFR at which the ratio is stoichiometric by using the lambda data and finding the value equal to 1. The stoichiometric AFR of the test engine used in this study is 14.52:1, this means that there are 14.52 units of air to 1 unit of fuel. The AFR Ratio can be worked out using Equation 1. The AFR at each RPM and load was supplied within the engine data and can be seen in Table 1.

$$AFR = \frac{M_{Air}}{M_{Fuel}}$$

Equation 1: Air:Fuel Ratio (Heywood, 1988)

Table 1: AFR

| Air:Fuel<br>Ratio in<br>Cylinder | RPM   |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |
|----------------------------------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
|                                  | 800   | 1000  | 1250  | 1500  | 1750  | 2000  | 2250  | 2500  | 3000  | 3500  | 4000  | 4500  | 5000  | 5500  | 6000  | 6500  |
| FL                               |       | 16.15 | 16.19 | 16.05 | 14.92 | 14.45 | 14.35 | 14.41 | 13.42 | 13.71 | 14.07 | 13.89 | 13.36 | 13.34 | 13.04 | 13.13 |
| 200                              |       |       |       |       |       | 14.45 | 14.29 | 14.42 | 13.78 | 14.41 |       |       |       |       |       |       |
| 190                              |       |       |       |       |       | 14.42 | 14.37 | 14.42 | 13.56 | 13.95 |       |       |       |       |       |       |
| 180                              |       |       |       |       | 14.89 | 14.43 | 14.45 | 14.41 | 14.03 | 13.79 | 14.05 |       |       |       |       |       |
| 170                              |       |       |       | 16.05 | 15.50 | 14.45 | 14.46 | 14.43 | 14.45 | 13.67 | 14.26 | 13.91 |       |       |       |       |
| 160                              |       |       |       | 16.11 | 15.62 | 14.52 | 14.49 | 14.42 | 14.46 | 14.45 | 14.44 | 13.99 | 13.52 |       |       |       |
| 150                              |       |       |       | 16.19 | 15.74 | 14.57 | 14.52 | 14.42 | 14.46 | 14.46 | 14.46 | 14.20 | 13.95 | 13.62 |       |       |
| 140                              |       |       | 16.09 | 16.08 | 15.77 | 14.58 | 14.55 | 14.49 | 14.49 | 14.45 | 14.46 | 14.47 | 14.36 | 13.92 | 13.27 |       |
| 130                              |       |       | 15.95 | 16.02 | 15.59 | 14.62 | 14.57 | 14.57 | 14.56 | 14.43 | 14.45 | 14.47 | 14.51 | 14.03 | 13.57 |       |
| 120                              |       |       | 15.88 | 15.57 | 14.73 | 14.68 | 14.62 | 14.60 | 14.60 | 14.43 | 14.46 | 14.52 | 14.52 | 14.27 | 13.77 | 13.50 |
| 110                              |       | 15.91 | 15.87 | 15.42 | 14.76 | 14.73 | 14.66 | 14.61 | 14.61 | 14.47 | 14.50 | 14.55 | 14.53 | 14.52 | 13.94 | 13.80 |
| 100                              |       | 14.94 | 15.68 | 14.75 | 14.80 | 14.74 | 14.65 | 14.62 | 14.62 | 14.59 | 14.59 | 14.61 | 14.58 | 14.56 | 14.39 | 13.81 |
| 90                               |       | 14.84 | 15.34 | 14.79 | 14.76 | 14.68 | 14.63 | 14.65 | 14.65 | 14.63 | 14.65 | 14.67 | 14.63 | 14.62 | 14.58 | 14.55 |
| 80                               |       | 14.75 | 14.71 | 14.73 | 14.70 | 14.68 | 14.67 | 14.67 | 14.68 | 14.68 | 14.69 | 14.72 | 14.67 | 14.64 | 14.63 | 14.60 |
| 70                               |       | 14.72 | 14.72 | 14.72 | 14.72 | 14.71 | 14.70 | 14.70 | 14.71 | 14.69 | 14.70 | 14.71 | 14.67 | 14.67 | 14.64 | 14.61 |
| 60                               |       | 14.72 | 14.73 | 14.72 | 14.71 | 14.70 | 14.70 | 14.72 | 14.72 | 14.71 | 14.70 | 14.69 | 14.68 | 14.67 | 14.66 | 14.62 |
| 50                               |       | 14.74 | 14.73 | 14.75 | 14.74 | 14.69 | 14.70 | 14.73 | 14.73 | 14.71 | 14.71 | 14.71 | 14.69 | 14.69 | 14.69 | 14.65 |
| 40                               | 14.63 | 14.76 | 14.76 | 14.74 | 14.73 | 14.72 | 14.72 | 14.74 | 14.73 | 14.73 | 14.72 | 14.72 | 14.70 | 14.69 | 14.75 | 14.71 |
| 30                               | 14.69 | 14.75 | 14.75 | 14.76 | 14.75 | 14.74 | 14.75 | 14.75 | 14.73 | 14.74 | 14.72 | 14.73 | 14.70 | 14.69 | 14.75 | 14.72 |
| 20                               | 14.66 | 14.68 | 14.73 | 14.75 | 14.74 | 14.76 | 14.76 | 14.76 | 14.75 | 14.74 | 14.73 | 14.73 | 14.68 | 14.68 | 14.70 | 14.67 |
| 10                               | 14.64 | 14.68 | 14.72 | 14.70 | 14.74 | 14.73 | 14.74 | 14.75 | 14.74 | 14.72 | 14.72 | 14.72 | 14.61 | 14.65 | 14.64 | 14.61 |
| 5                                | 14.56 | 14.66 | 14.70 | 14.69 | 14.71 | 14.72 | 14.73 | 14.74 | 14.73 | 14.72 | 14.71 | 14.72 | 14.58 | 14.59 | 14.56 | 14.58 |
| 2                                | 14.58 | 14.67 | 14.71 | 14.71 | 14.72 | 14.73 | 14.73 | 14.76 | 14.72 | 14.70 | 14.70 | 14.70 |       |       |       |       |

The AFR of an engine is dependent on the load and requirements of the engine, therefore the ECU will alter it to suit demand. The specific fuel consumption is directly affected by the AFR, the leaner the engine is run, the less fuel is used, however there is less power produced. The richer the engine is run, the more power is produced, however the fuel consumption also rises. This is illustrated in Figure 1.

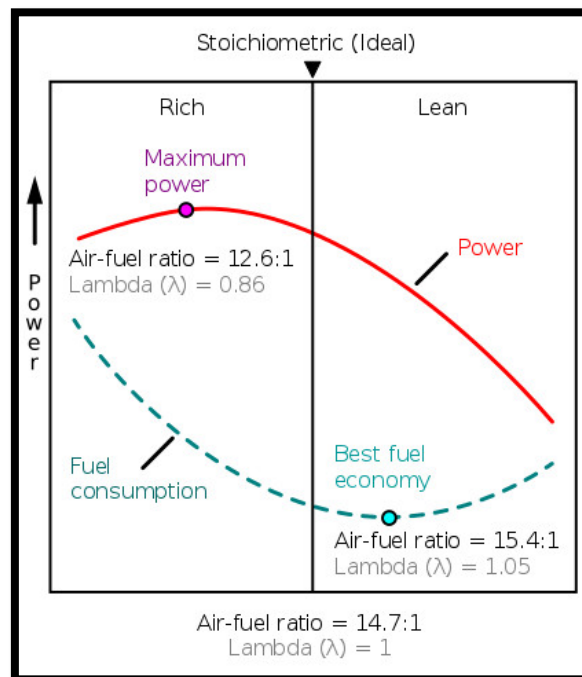


Figure 1: Rich and Lean AFR and Lambda Comparison (X-Engineer, 2018)

## 1.2 Lambda $\lambda$

The lambda value represents the ratio of oxygen present in perfect combustion compared to that which is present in the cylinder. In perfect combustion the value of lambda will be 1, if value is larger than 1 then the mixture is lean, if it is lower than 1, then the mixture is rich (Robert Bosch, 2011). lambda is measured by a sensor in the exhaust which then relays the data back to the ECU which alters the AFR accordingly. Lambda can be calculated in several ways shown in Equation 2 and Equation 3. The AFR at each RPM and load was supplied within the engine data and was also checked using Equation 2 and Equation 3 and can be seen in Table 2.

$$\lambda = \frac{AFR_{Actual}}{AFR_{Ideal}}$$

Equation 2: Lambda using AFR (X-Engineer, 2018)

or

$$\lambda = \frac{1}{FER}$$

Equation 3: Lambda using FER (Heywood, 1988)

Table 2: Lambda Data

| Lambda ( $\lambda$ )<br>Calculated | RPM  |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |
|------------------------------------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|
|                                    | 800  | 1000 | 1250 | 1500 | 1750 | 2000 | 2250 | 2500 | 3000 | 3500 | 4000 | 4500 | 5000 | 5500 | 6000 | 6500 |
| FL                                 |      | 1.11 | 1.12 | 1.11 | 1.03 | 1.00 | 0.99 | 0.99 | 0.92 | 0.94 | 0.97 | 0.96 | 0.92 | 0.92 | 0.90 | 0.90 |
| 200                                |      |      |      |      |      | 1.00 | 0.98 | 0.99 | 0.95 | 0.99 |      |      |      |      |      |      |
| 190                                |      |      |      |      |      | 0.99 | 0.99 | 0.99 | 0.93 | 0.96 |      |      |      |      |      |      |
| 180                                |      |      |      |      | 1.03 | 0.99 | 1.00 | 0.99 | 0.97 | 0.95 | 0.97 |      |      |      |      |      |
| 170                                |      |      |      | 1.11 | 1.07 | 1.00 | 1.00 | 0.99 | 1.00 | 0.94 | 0.98 | 0.96 |      |      |      |      |
| 160                                |      |      |      | 1.11 | 1.08 | 1.00 | 1.00 | 0.99 | 1.00 | 1.00 | 0.99 | 0.96 | 0.93 |      |      |      |
| 150                                |      |      |      | 1.12 | 1.08 | 1.00 | 1.00 | 0.99 | 1.00 | 1.00 | 1.00 | 0.98 | 0.96 | 0.94 |      |      |
| 140                                |      |      | 1.11 | 1.11 | 1.09 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 0.99 | 0.96 | 0.91 |      |
| 130                                |      |      | 1.10 | 1.10 | 1.07 | 1.01 | 1.00 | 1.00 | 1.00 | 0.99 | 1.00 | 1.00 | 1.00 | 0.97 | 0.93 |      |
| 120                                |      |      | 1.09 | 1.07 | 1.01 | 1.01 | 1.01 | 1.01 | 1.01 | 0.99 | 1.00 | 1.00 | 1.00 | 0.98 | 0.95 | 0.93 |
| 110                                |      | 1.10 | 1.09 | 1.06 | 1.02 | 1.01 | 1.01 | 1.01 | 1.01 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 0.96 | 0.95 |
| 100                                |      | 1.03 | 1.08 | 1.02 | 1.02 | 1.02 | 1.01 | 1.01 | 1.01 | 1.00 | 1.00 | 1.01 | 1.00 | 1.00 | 0.99 | 0.95 |
| 90                                 |      | 1.02 | 1.06 | 1.02 | 1.02 | 1.01 | 1.01 | 1.01 | 1.01 | 1.01 | 1.01 | 1.01 | 1.01 | 1.01 | 1.00 | 1.00 |
| 80                                 |      | 1.02 | 1.01 | 1.01 | 1.01 | 1.01 | 1.01 | 1.01 | 1.01 | 1.01 | 1.01 | 1.01 | 1.01 | 1.01 | 1.01 | 1.01 |
| 70                                 |      | 1.01 | 1.01 | 1.01 | 1.01 | 1.01 | 1.01 | 1.01 | 1.01 | 1.01 | 1.01 | 1.01 | 1.01 | 1.01 | 1.01 | 1.01 |
| 60                                 |      | 1.01 | 1.01 | 1.01 | 1.01 | 1.01 | 1.01 | 1.01 | 1.01 | 1.01 | 1.01 | 1.01 | 1.01 | 1.01 | 1.01 | 1.01 |
| 50                                 |      | 1.02 | 1.01 | 1.02 | 1.02 | 1.01 | 1.01 | 1.01 | 1.01 | 1.01 | 1.01 | 1.01 | 1.01 | 1.01 | 1.01 | 1.01 |
| 40                                 | 1.01 | 1.02 | 1.02 | 1.02 | 1.01 | 1.01 | 1.01 | 1.02 | 1.01 | 1.01 | 1.01 | 1.01 | 1.01 | 1.01 | 1.02 | 1.01 |
| 30                                 | 1.01 | 1.02 | 1.02 | 1.02 | 1.02 | 1.02 | 1.02 | 1.02 | 1.01 | 1.02 | 1.01 | 1.01 | 1.01 | 1.01 | 1.02 | 1.01 |
| 20                                 | 1.01 | 1.01 | 1.01 | 1.02 | 1.02 | 1.02 | 1.02 | 1.02 | 1.02 | 1.02 | 1.01 | 1.01 | 1.01 | 1.01 | 1.01 | 1.01 |
| 10                                 | 1.01 | 1.01 | 1.01 | 1.01 | 1.02 | 1.01 | 1.02 | 1.02 | 1.02 | 1.01 | 1.01 | 1.01 | 1.01 | 1.01 | 1.01 | 1.01 |
| 5                                  | 1.00 | 1.01 | 1.01 | 1.01 | 1.01 | 1.01 | 1.01 | 1.02 | 1.01 | 1.01 | 1.01 | 1.01 | 1.00 | 1.00 | 1.00 | 1.00 |
| 2                                  | 1.00 | 1.01 | 1.01 | 1.01 | 1.01 | 1.01 | 1.01 | 1.02 | 1.01 | 1.01 | 1.01 | 1.01 |      |      |      |      |

### 1.3 Fuel Equivalence Ratio $\phi$

The FER is another way of representing the composition of the air:fuel mixture within the cylinder and determining if it is rich, lean or stoichiometric. If the FER is greater than 1, then the mixture is rich, whereas if it is less than 1, the mixture is lean. As with lambda, if the FER is equal to 1 then the mixture is stoichiometric (Turns, 2006). As can be seen the FER is the inverse of the lambda value. The FER is defined as the ratio of the actual AFR by the theoretical AFR. The FER is calculated using Equation 4 and Equation 5. The calculated FER is shown in Table 3 and is used in calculations throughout the study.

$$\phi = \frac{AFR_{Ideal}}{AFR_{Actual}}$$

Equation 4: FER using AFR (Turns, 2006)

or

$$\phi = \frac{1}{\lambda}$$

Equation 5: FER using  $\lambda$  (Heywood, 1988)

Table 3: Fuel Equivalence Ratio

| Fuel<br>Equivalence<br>Ratio ( $\phi$ ) | RPM   |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |
|-----------------------------------------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
|                                         | 800   | 1000  | 1250  | 1500  | 1750  | 2000  | 2250  | 2500  | 3000  | 3500  | 4000  | 4500  | 5000  | 5500  | 6000  | 6500  |
| FL                                      |       | 0.899 | 0.897 | 0.905 | 0.973 | 1.005 | 1.012 | 1.008 | 1.082 | 1.059 | 1.032 | 1.045 | 1.087 | 1.088 | 1.113 | 1.106 |
| 200                                     |       |       |       |       |       | 1.005 | 1.016 | 1.007 | 1.054 | 1.008 |       |       |       |       |       |       |
| 190                                     |       |       |       |       |       | 1.007 | 1.010 | 1.007 | 1.071 | 1.041 |       |       |       |       |       |       |
| 180                                     |       |       |       |       | 0.975 | 1.006 | 1.005 | 1.008 | 1.035 | 1.053 | 1.033 |       |       |       |       |       |
| 170                                     |       |       |       | 0.905 | 0.937 | 1.005 | 1.004 | 1.006 | 1.005 | 1.062 | 1.018 | 1.044 |       |       |       |       |
| 160                                     |       |       |       | 0.901 | 0.930 | 1.000 | 1.002 | 1.007 | 1.004 | 1.005 | 1.006 | 1.038 | 1.074 |       |       |       |
| 150                                     |       |       |       | 0.897 | 0.922 | 0.997 | 1.000 | 1.007 | 1.004 | 1.004 | 1.004 | 1.023 | 1.041 | 1.066 |       |       |
| 140                                     |       |       | 0.902 | 0.903 | 0.921 | 0.996 | 0.998 | 1.002 | 1.002 | 1.005 | 1.004 | 1.003 | 1.011 | 1.043 | 1.094 |       |
| 130                                     |       |       | 0.910 | 0.906 | 0.931 | 0.993 | 0.997 | 0.997 | 0.997 | 1.006 | 1.005 | 1.003 | 1.001 | 1.035 | 1.070 |       |
| 120                                     |       |       | 0.914 | 0.933 | 0.986 | 0.989 | 0.993 | 0.995 | 0.995 | 1.006 | 1.004 | 1.000 | 1.000 | 1.018 | 1.054 | 1.076 |
| 110                                     |       | 0.913 | 0.915 | 0.942 | 0.984 | 0.986 | 0.990 | 0.994 | 0.994 | 1.003 | 1.001 | 0.998 | 0.999 | 1.000 | 1.042 | 1.052 |
| 100                                     |       | 0.972 | 0.926 | 0.984 | 0.981 | 0.985 | 0.991 | 0.993 | 0.993 | 0.995 | 0.995 | 0.994 | 0.996 | 0.997 | 1.009 | 1.051 |
| 90                                      |       | 0.978 | 0.947 | 0.982 | 0.984 | 0.989 | 0.992 | 0.991 | 0.991 | 0.992 | 0.991 | 0.990 | 0.992 | 0.993 | 0.996 | 0.998 |
| 80                                      |       | 0.984 | 0.987 | 0.986 | 0.988 | 0.989 | 0.990 | 0.990 | 0.989 | 0.989 | 0.988 | 0.986 | 0.990 | 0.992 | 0.992 | 0.995 |
| 70                                      |       | 0.986 | 0.986 | 0.986 | 0.986 | 0.987 | 0.988 | 0.988 | 0.987 | 0.988 | 0.988 | 0.987 | 0.990 | 0.990 | 0.992 | 0.994 |
| 60                                      |       | 0.986 | 0.986 | 0.986 | 0.987 | 0.988 | 0.988 | 0.986 | 0.986 | 0.987 | 0.988 | 0.988 | 0.989 | 0.990 | 0.990 | 0.993 |
| 50                                      |       | 0.985 | 0.986 | 0.984 | 0.985 | 0.988 | 0.988 | 0.986 | 0.986 | 0.987 | 0.987 | 0.987 | 0.988 | 0.988 | 0.988 | 0.991 |
| 40                                      | 0.992 | 0.984 | 0.984 | 0.985 | 0.986 | 0.986 | 0.986 | 0.985 | 0.986 | 0.986 | 0.986 | 0.986 | 0.988 | 0.988 | 0.984 | 0.987 |
| 30                                      | 0.988 | 0.984 | 0.984 | 0.984 | 0.984 | 0.985 | 0.984 | 0.984 | 0.986 | 0.985 | 0.986 | 0.986 | 0.988 | 0.988 | 0.984 | 0.986 |
| 20                                      | 0.990 | 0.989 | 0.986 | 0.984 | 0.985 | 0.984 | 0.984 | 0.984 | 0.984 | 0.985 | 0.986 | 0.986 | 0.989 | 0.989 | 0.988 | 0.990 |
| 10                                      | 0.992 | 0.989 | 0.986 | 0.988 | 0.985 | 0.986 | 0.985 | 0.984 | 0.985 | 0.986 | 0.986 | 0.986 | 0.994 | 0.991 | 0.992 | 0.994 |
| 5                                       | 0.997 | 0.990 | 0.988 | 0.988 | 0.987 | 0.986 | 0.986 | 0.985 | 0.986 | 0.986 | 0.987 | 0.986 | 0.996 | 0.995 | 0.997 | 0.996 |
| 2                                       | 0.996 | 0.990 | 0.987 | 0.987 | 0.986 | 0.986 | 0.986 | 0.984 | 0.986 | 0.988 | 0.988 | 0.988 |       |       |       |       |

## 1.4 Air:Fuel Mass

The mass of fuel that is injected into the engine per hour was supplied in the Ford data. To be used in the calculations this was converted from Kg/Hour to Kg/Cylinder per revolution. This was done by using Equation 6. The resulting fuel mass in Kg/Cylinder can be seen in Table 4.

$$\text{Fuel Mass (Kg/Cylinder)} = \frac{\text{Fuel Mass (Kg/Hour)}}{60 \times \text{RPM}} \div 1.5$$

Equation 6: Fuel Mass Conversion

Table 4: Fuel Mass (Kg/Cylinder)

| Fuel Mass<br>Kg/Cylinder | RPM       |           |           |           |           |           |           |           |           |           |           |           |           |           |           |
|--------------------------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|
|                          | 800       | 1000      | 1250      | 1500      | 1750      | 2000      | 2250      | 2500      | 3000      | 3500      | 4000      | 4500      | 5000      | 5500      | 6000      |
| FL                       |           | 0.0000360 | 0.0000464 | 0.0000557 | 0.0000596 | 0.0000631 | 0.0000638 | 0.0000637 | 0.0000670 | 0.0000601 | 0.0000598 | 0.0000552 | 0.0000568 | 0.0000538 | 0.0000511 |
| 200                      |           |           |           |           |           | 0.0000630 | 0.0000640 | 0.0000633 | 0.0000659 | 0.0000618 |           |           |           |           |           |
| 190                      |           |           |           |           |           | 0.0000598 | 0.0000595 | 0.0000595 | 0.0000626 | 0.0000586 |           |           |           |           |           |
| 180                      |           |           |           |           | 0.0000578 | 0.0000558 | 0.0000556 | 0.0000556 | 0.0000564 | 0.0000564 | 0.0000573 |           |           |           |           |
| 170                      |           |           |           | 0.0000556 | 0.0000557 | 0.0000521 | 0.0000520 | 0.0000521 | 0.0000521 | 0.0000544 | 0.0000525 | 0.0000529 |           |           |           |
| 160                      |           |           |           | 0.0000526 | 0.0000513 | 0.0000486 | 0.0000482 | 0.0000484 | 0.0000483 | 0.0000478 | 0.0000485 | 0.0000489 | 0.0000526 |           |           |
| 150                      |           |           |           | 0.0000483 | 0.0000474 | 0.0000454 | 0.0000450 | 0.0000453 | 0.0000444 | 0.0000444 | 0.0000449 | 0.0000448 | 0.0000466 | 0.0000494 |           |
| 140                      |           |           | 0.0000461 | 0.0000447 | 0.0000434 | 0.0000424 | 0.0000417 | 0.0000420 | 0.0000408 | 0.0000410 | 0.0000413 | 0.0000411 | 0.0000420 | 0.0000437 | 0.0000474 |
| 130                      |           |           | 0.0000420 | 0.0000404 | 0.0000391 | 0.0000387 | 0.0000382 | 0.0000380 | 0.0000372 | 0.0000377 | 0.0000384 | 0.0000380 | 0.0000384 | 0.0000398 | 0.0000425 |
| 120                      |           |           | 0.0000387 | 0.0000365 | 0.0000365 | 0.0000355 | 0.0000349 | 0.0000346 | 0.0000339 | 0.0000348 | 0.0000357 | 0.0000352 | 0.0000353 | 0.0000364 | 0.0000379 |
| 110                      |           | 0.0000358 | 0.0000348 | 0.0000335 | 0.0000333 | 0.0000321 | 0.0000318 | 0.0000317 | 0.0000312 | 0.0000317 | 0.0000324 | 0.0000322 | 0.0000324 | 0.0000329 | 0.0000346 |
| 100                      |           | 0.0000330 | 0.0000305 | 0.0000306 | 0.0000296 | 0.0000289 | 0.0000285 | 0.0000288 | 0.0000286 | 0.0000287 | 0.0000293 | 0.0000293 | 0.0000297 | 0.0000303 | 0.0000311 |
| 90                       |           | 0.0000284 | 0.0000267 | 0.0000267 | 0.0000261 | 0.0000253 | 0.0000253 | 0.0000256 | 0.0000256 | 0.0000258 | 0.0000260 | 0.0000264 | 0.0000269 | 0.0000275 | 0.0000281 |
| 80                       |           | 0.0000244 | 0.0000236 | 0.0000233 | 0.0000228 | 0.0000225 | 0.0000225 | 0.0000228 | 0.0000226 | 0.0000226 | 0.0000233 | 0.0000236 | 0.0000243 | 0.0000249 | 0.0000253 |
| 70                       |           | 0.0000210 | 0.0000207 | 0.0000205 | 0.0000204 | 0.0000200 | 0.0000201 | 0.0000203 | 0.0000200 | 0.0000201 | 0.0000207 | 0.0000208 | 0.0000216 | 0.0000221 | 0.0000226 |
| 60                       |           | 0.0000181 | 0.0000180 | 0.0000179 | 0.0000177 | 0.0000173 | 0.0000175 | 0.0000179 | 0.0000176 | 0.0000176 | 0.0000181 | 0.0000182 | 0.0000189 | 0.0000194 | 0.0000199 |
| 50                       |           | 0.0000153 | 0.0000154 | 0.0000154 | 0.0000151 | 0.0000150 | 0.0000150 | 0.0000152 | 0.0000151 | 0.0000152 | 0.0000156 | 0.0000158 | 0.0000162 | 0.0000167 | 0.0000173 |
| 40                       | 0.0000144 | 0.0000129 | 0.0000130 | 0.0000130 | 0.0000128 | 0.0000127 | 0.0000127 | 0.0000128 | 0.0000128 | 0.0000130 | 0.0000133 | 0.0000135 | 0.0000139 | 0.0000143 | 0.0000147 |
| 30                       | 0.0000124 | 0.0000106 | 0.0000106 | 0.0000105 | 0.0000106 | 0.0000104 | 0.0000105 | 0.0000105 | 0.0000106 | 0.0000108 | 0.0000109 | 0.0000112 | 0.0000116 | 0.0000120 | 0.0000123 |
| 20                       | 0.0000085 | 0.0000081 | 0.0000083 | 0.0000081 | 0.0000083 | 0.0000082 | 0.0000081 | 0.0000082 | 0.0000082 | 0.0000085 | 0.0000087 | 0.0000090 | 0.0000093 | 0.0000096 | 0.0000099 |
| 10                       | 0.0000061 | 0.0000057 | 0.0000058 | 0.0000058 | 0.0000059 | 0.0000058 | 0.0000057 | 0.0000057 | 0.0000060 | 0.0000061 | 0.0000066 | 0.0000067 | 0.0000071 | 0.0000074 | 0.0000077 |
| 5                        | 0.0000050 | 0.0000047 | 0.0000047 | 0.0000047 | 0.0000050 | 0.0000049 | 0.0000048 | 0.0000048 | 0.0000049 | 0.0000051 | 0.0000055 | 0.0000058 | 0.0000061 | 0.0000063 | 0.0000066 |
| 2                        | 0.0000044 | 0.0000043 | 0.0000041 | 0.0000041 | 0.0000042 | 0.0000043 | 0.0000042 | 0.0000044 | 0.0000045 | 0.0000046 | 0.0000051 | 0.0000052 |           |           |           |

The fuel mass was then used to calculate the mass of the air within the cylinder. This was achieved using the AFR and can be seen in Equation 7. The results can be seen Table 5.

$$\text{Air Mass (Kg/Cylinder)} = \text{Fuel Mass (Kg/Cylinder)} \times \text{AFR}$$

Equation 7: Air Mass (Kg/Cylinder)

Table 5: Air Mass (Kg/Cylinder)

| Calculated Air Mass<br>Kg/Cylinder | RPM       |           |           |           |           |           |           |           |           |           |           |           |           |           |           |           |
|------------------------------------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|
|                                    | 800       | 1000      | 1250      | 1500      | 1750      | 2000      | 2250      | 2500      | 3000      | 3500      | 4000      | 4500      | 5000      | 5500      | 6000      | 6500      |
| FL                                 |           | 0.0005814 | 0.0007512 | 0.0008940 | 0.0008895 | 0.0009112 | 0.0009156 | 0.0009184 | 0.0008986 | 0.0008235 | 0.0008419 | 0.0007662 | 0.0007586 | 0.0007171 | 0.0006670 | 0.0005636 |
| 200                                |           |           |           |           |           | 0.0009104 | 0.0009146 | 0.0009133 | 0.0009074 | 0.0008907 |           |           |           |           |           |           |
| 190                                |           |           |           |           |           | 0.0008628 | 0.0008544 | 0.0008582 | 0.0008493 | 0.0008175 |           |           |           |           |           |           |
| 180                                |           |           |           |           | 0.0008613 | 0.0008057 | 0.0008035 | 0.0008018 | 0.0007919 | 0.0007775 | 0.0008044 |           |           |           |           |           |
| 170                                |           |           |           | 0.0008929 | 0.0008631 | 0.0007530 | 0.0007512 | 0.0007516 | 0.0007525 | 0.0007438 | 0.0007490 | 0.0007353 |           |           |           |           |
| 160                                |           |           |           | 0.0008473 | 0.0008013 | 0.0007050 | 0.0006991 | 0.0006973 | 0.0006989 | 0.0006908 | 0.0007003 | 0.0006840 | 0.0007115 |           |           |           |
| 150                                |           |           |           | 0.0007819 | 0.0007455 | 0.0006613 | 0.0006539 | 0.0006531 | 0.0006416 | 0.0006427 | 0.0006499 | 0.0006364 | 0.0006507 | 0.0006733 |           |           |
| 140                                |           |           | 0.0007423 | 0.0007194 | 0.0006849 | 0.0006180 | 0.0006071 | 0.0006079 | 0.0005909 | 0.0005931 | 0.0005973 | 0.0005949 | 0.0006038 | 0.0006083 | 0.0006286 |           |
| 130                                |           |           | 0.0006706 | 0.0006479 | 0.0006097 | 0.0005653 | 0.0005562 | 0.0005537 | 0.0005420 | 0.0005447 | 0.0005555 | 0.0005502 | 0.0005578 | 0.0005586 | 0.0005762 |           |
| 120                                |           |           | 0.0006140 | 0.0005686 | 0.0005378 | 0.0005211 | 0.0005104 | 0.0005055 | 0.0004948 | 0.0005016 | 0.0005165 | 0.0005105 | 0.0005124 | 0.0005189 | 0.0005215 | 0.0005377 |
| 110                                |           | 0.0005692 | 0.0005516 | 0.0005163 | 0.0004911 | 0.0004730 | 0.0004655 | 0.0004630 | 0.0004556 | 0.0004580 | 0.0004692 | 0.0004692 | 0.0004708 | 0.0004784 | 0.0004817 | 0.0004930 |
| 100                                |           | 0.0004930 | 0.0004781 | 0.0004512 | 0.0004379 | 0.0004258 | 0.0004182 | 0.0004211 | 0.0004175 | 0.0004182 | 0.0004268 | 0.0004286 | 0.0004335 | 0.0004412 | 0.0004472 | 0.0004535 |
| 90                                 |           | 0.0004221 | 0.0004091 | 0.0003944 | 0.0003852 | 0.0003711 | 0.0003706 | 0.0003757 | 0.0003744 | 0.0003739 | 0.0003809 | 0.0003876 | 0.0003937 | 0.0004014 | 0.0004091 | 0.0004216 |
| 80                                 |           | 0.0003606 | 0.0003478 | 0.0003437 | 0.0003351 | 0.0003303 | 0.0003296 | 0.0003345 | 0.0003322 | 0.0003323 | 0.0003424 | 0.0003475 | 0.0003570 | 0.0003644 | 0.0003695 | 0.0003806 |
| 70                                 |           | 0.0003091 | 0.0003049 | 0.0003020 | 0.0003000 | 0.0002942 | 0.0002955 | 0.0002979 | 0.0002942 | 0.0002947 | 0.0003042 | 0.0003065 | 0.0003165 | 0.0003236 | 0.0003302 | 0.0003419 |
| 60                                 |           | 0.0002666 | 0.0002645 | 0.0002639 | 0.0002596 | 0.0002548 | 0.0002570 | 0.0002630 | 0.0002590 | 0.0002587 | 0.0002654 | 0.0002680 | 0.0002776 | 0.0002845 | 0.0002921 | 0.0003009 |
| 50                                 |           | 0.0002260 | 0.0002265 | 0.0002273 | 0.0002227 | 0.0002204 | 0.0002200 | 0.0002232 | 0.0002231 | 0.0002242 | 0.0002288 | 0.0002328 | 0.0002386 | 0.0002448 | 0.0002538 | 0.0002609 |
| 40                                 | 0.0002113 | 0.0001902 | 0.0001916 | 0.0001922 | 0.0001880 | 0.0001865 | 0.0001868 | 0.0001880 | 0.0001888 | 0.0001917 | 0.0001950 | 0.0001992 | 0.0002048 | 0.0002107 | 0.0002169 | 0.0002243 |
| 30                                 | 0.0001816 | 0.0001557 | 0.0001580 | 0.0001553 | 0.0001564 | 0.0001540 | 0.0001551 | 0.0001547 | 0.0001555 | 0.0001596 | 0.0001611 | 0.0001655 | 0.0001702 | 0.0001763 | 0.0001808 | 0.0001890 |
| 20                                 | 0.0001242 | 0.0001191 | 0.0001218 | 0.0001202 | 0.0001217 | 0.0001214 | 0.0001203 | 0.0001207 | 0.0001207 | 0.0001249 | 0.0001281 | 0.0001324 | 0.0001364 | 0.0001412 | 0.0001462 | 0.0001525 |
| 10                                 | 0.0000895 | 0.0000832 | 0.0000850 | 0.0000849 | 0.0000870 | 0.0000859 | 0.0000844 | 0.0000846 | 0.0000890 | 0.0000897 | 0.0000973 | 0.0000989 | 0.0001032 | 0.0001077 | 0.0001133 | 0.0001196 |
| 5                                  | 0.0000728 | 0.0000684 | 0.0000693 | 0.0000686 | 0.0000738 | 0.0000720 | 0.0000713 | 0.0000714 | 0.0000720 | 0.0000748 | 0.0000813 | 0.0000847 | 0.0000885 | 0.0000926 | 0.0000960 | 0.0001017 |
| 2                                  | 0.0000648 | 0.0000636 | 0.0000601 | 0.0000610 | 0.0000617 | 0.0000638 | 0.0000626 | 0.0000643 | 0.0000665 | 0.0000672 | 0.0000747 | 0.0000759 |           |           |           |           |

The fuel mass and air mass are then combined to give the air:fuel mass Kg/Cylinder. The results can be seen in Table 6.

Table 6: Air:Fuel Mass (Kg/Cylinder)

| Air:Fuel Mass<br>kg/Cylinder | RPM       |           |           |           |           |           |           |           |           |           |           |           |           |           |           |           |
|------------------------------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|
|                              | 800       | 1000      | 1250      | 1500      | 1750      | 2000      | 2250      | 2500      | 3000      | 3500      | 4000      | 4500      | 5000      | 5500      | 6000      | 6500      |
| FL                           |           | 0.0006174 | 0.0007976 | 0.0009497 | 0.0009491 | 0.0009742 | 0.0009794 | 0.0009821 | 0.0009656 | 0.0008835 | 0.0009017 | 0.0008213 | 0.0008153 | 0.0007709 | 0.0007181 | 0.0006065 |
| 200                          |           |           |           |           |           | 0.0009734 | 0.0009786 | 0.0009766 | 0.0009733 | 0.0009525 |           |           |           |           |           |           |
| 190                          |           |           |           |           |           | 0.0009226 | 0.0009139 | 0.0009177 | 0.0009119 | 0.0008761 |           |           |           |           |           |           |
| 180                          |           |           |           |           | 0.0009191 | 0.0008615 | 0.0008591 | 0.0008575 | 0.0008484 | 0.0008339 | 0.0008616 |           |           |           |           |           |
| 170                          |           |           |           | 0.0009485 | 0.0009188 | 0.0008051 | 0.0008032 | 0.0008037 | 0.0008045 | 0.0007982 | 0.0008016 | 0.0007882 |           |           |           |           |
| 160                          |           |           |           | 0.0008999 | 0.0008526 | 0.0007536 | 0.0007473 | 0.0007456 | 0.0007472 | 0.0007387 | 0.0007488 | 0.0007328 | 0.0007641 |           |           |           |
| 150                          |           |           |           | 0.0008302 | 0.0007929 | 0.0007067 | 0.0006990 | 0.0006984 | 0.0006860 | 0.0006871 | 0.0006948 | 0.0006812 | 0.0006973 | 0.0007227 |           |           |
| 140                          |           |           | 0.0007884 | 0.0007642 | 0.0007263 | 0.0006604 | 0.0006489 | 0.0006499 | 0.0006316 | 0.0006342 | 0.0006386 | 0.0006380 | 0.0006458 | 0.0006520 | 0.0006760 |           |
| 130                          |           |           | 0.0007127 | 0.0006884 | 0.0006489 | 0.0006040 | 0.0005944 | 0.0005917 | 0.0005792 | 0.0005824 | 0.0005940 | 0.0005882 | 0.0005963 | 0.0005985 | 0.0006187 |           |
| 120                          |           |           | 0.0006527 | 0.0006051 | 0.0005743 | 0.0005566 | 0.0005454 | 0.0005401 | 0.0005287 | 0.0005364 | 0.0005523 | 0.0005457 | 0.0005477 | 0.0005553 | 0.0005593 | 0.0005775 |
| 110                          |           | 0.0006050 | 0.0005863 | 0.0005498 | 0.0005243 | 0.0005051 | 0.0004973 | 0.0004947 | 0.0004868 | 0.0004896 | 0.0005016 | 0.0005014 | 0.0005032 | 0.0005114 | 0.0005163 | 0.0005288 |
| 100                          |           | 0.0005260 | 0.0005086 | 0.0004818 | 0.0004675 | 0.0004547 | 0.0004467 | 0.0004499 | 0.0004460 | 0.0004469 | 0.0004560 | 0.0004579 | 0.0004632 | 0.0004715 | 0.0004782 | 0.0004863 |
| 90                           |           | 0.0004506 | 0.0004357 | 0.0004211 | 0.0004113 | 0.0003964 | 0.0003960 | 0.0004013 | 0.0003999 | 0.0003994 | 0.0004069 | 0.0004140 | 0.0004206 | 0.0004288 | 0.0004371 | 0.0004506 |
| 80                           |           | 0.0003850 | 0.0003715 | 0.0003670 | 0.0003579 | 0.0003528 | 0.0003521 | 0.0003573 | 0.0003548 | 0.0003549 | 0.0003657 | 0.0003711 | 0.0003813 | 0.0003893 | 0.0003948 | 0.0004067 |
| 70                           |           | 0.0003301 | 0.0003256 | 0.0003226 | 0.0003204 | 0.0003142 | 0.0003156 | 0.0003182 | 0.0003142 | 0.0003148 | 0.0003249 | 0.0003274 | 0.0003381 | 0.0003457 | 0.0003528 | 0.0003653 |
| 60                           |           | 0.0002847 | 0.0002824 | 0.0002818 | 0.0002773 | 0.0002721 | 0.0002745 | 0.0002809 | 0.0002766 | 0.0002763 | 0.0002835 | 0.0002863 | 0.0002965 | 0.0003039 | 0.0003120 | 0.0003215 |
| 50                           |           | 0.0002413 | 0.0002419 | 0.0002427 | 0.0002378 | 0.0002354 | 0.0002349 | 0.0002384 | 0.0002383 | 0.0002394 | 0.0002444 | 0.0002486 | 0.0002549 | 0.0002615 | 0.0002711 | 0.0002788 |
| 40                           | 0.0002258 | 0.0002031 | 0.0002045 | 0.0002052 | 0.0002007 | 0.0001991 | 0.0001995 | 0.0002008 | 0.0002016 | 0.0002047 | 0.0002083 | 0.0002127 | 0.0002188 | 0.0002250 | 0.0002316 | 0.0002395 |
| 30                           | 0.0001939 | 0.0001663 | 0.0001666 | 0.0001658 | 0.0001670 | 0.0001644 | 0.0001657 | 0.0001652 | 0.0001660 | 0.0001704 | 0.0001720 | 0.0001767 | 0.0001818 | 0.0001883 | 0.0001931 | 0.0002018 |
| 20                           | 0.0001327 | 0.0001272 | 0.0001300 | 0.0001283 | 0.0001299 | 0.0001296 | 0.0001284 | 0.0001289 | 0.0001289 | 0.0001334 | 0.0001368 | 0.0001414 | 0.0001456 | 0.0001508 | 0.0001561 | 0.0001629 |
| 10                           | 0.0000956 | 0.0000889 | 0.0000908 | 0.0000907 | 0.0000929 | 0.0000918 | 0.0000902 | 0.0000903 | 0.0000950 | 0.0000958 | 0.0001039 | 0.0001056 | 0.0001103 | 0.0001151 | 0.0001211 | 0.0001278 |
| 5                            | 0.0000778 | 0.0000731 | 0.0000740 | 0.0000732 | 0.0000788 | 0.0000769 | 0.0000761 | 0.0000763 | 0.0000769 | 0.0000798 | 0.0000868 | 0.0000904 | 0.0000945 | 0.0000989 | 0.0001026 | 0.0001087 |
| 2                            | 0.0000692 | 0.0000679 | 0.0000642 | 0.0000652 | 0.0000659 | 0.0000682 | 0.0000668 | 0.0000686 | 0.0000710 | 0.0000718 | 0.0000798 | 0.0000810 |           |           |           |           |

## 1.5 Reactants and Products

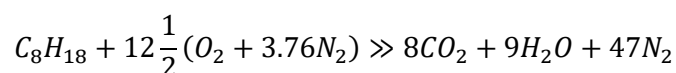
It is assumed that the fuel used in the engine test from which the data was gathered is Isooctane with the formula  $C_8H_{18}$ . Using this assumption, it is possible to calculate the quantity of air required for the stoichiometric combustion of the Isooctane. The quantities obtained can then be used to calculate the reactants at various AFRs. The nature of the relationship between the reactants and products of combustion is dependent on the conservation of mass, meaning that only the proportions of the air:fuel mixture and chemical composition are required. Because of this, the products of combustion can also be calculated at the various loads and AFRs (Heywood, 1988).

The following steps are used to obtain the quantity of air in the stoichiometric combustion of  $C_8H_{18}$ , it is known that the products of combustion are  $CO_2$  and  $H_2O$  (Heywood, 1988):

$$\begin{aligned} 1. \quad & C_8H_{18} + \left( \left( x + \frac{y}{2} \times O_2 \right) \right) \gg (x \times CO_2) + (y \times H_2O) \\ 2. \quad & C_8H_{18} + (12.5O_2) \gg (8CO_2) + (9H_2O) \end{aligned}$$

*Equation 8:  $C_8H_{18}$  Reactant and Product Calculation (Heywood, 1988)*

Air is composed of 20.94% Oxygen, 78.08% of air is Nitrogen, therefore the Nitrogen content of air is also considered in this study. There are several other elements present but they are in such small proportions they are considered negligible (Helmenstine, 2017). Due to there being approximately 3.7 times as much Nitrogen in the air as Oxygen, Equation 8 is adapted for the stoichiometric combustion of  $C_8H_{18}$  with the inclusion of Nitrogen and can be seen in Equation 9.



*Equation 9:  $C_8H_{18}$  Stoichiometric Combustion Reactants and Products (Heywood, 1988)*

Using Equation 9 it is possible to calculate what the composition of the air:fuel mixture at different AFRs. This is done by using the FER. By altering the FER, the amount of Carbon and Hydrogen reactants in the calculation changes, however the Oxygen and Nitrogen content will remain the same due to the calculation being based off the ratio of fuel to air and therefore the quantity of Oxygen present at each load and RPM is 25 and likewise the quantity of Nitrogen present is 47. Table 7 and Table 8 show the quantity of Carbon and Hydrogen reactants at the different AFRs for each load and RPM previously calculated.

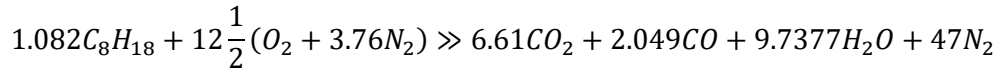
Table 7: Reactant Quantity - Carbon

| Reactant Carbon (C) | RPM  |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |
|---------------------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|
|                     | 800  | 1000 | 1250 | 1500 | 1750 | 2000 | 2250 | 2500 | 3000 | 3500 | 4000 | 4500 | 5000 | 5500 | 6000 | 6500 |
| FL                  |      | 7.19 | 7.17 | 7.24 | 7.79 | 8.04 | 8.09 | 8.06 | 8.66 | 8.47 | 8.26 | 8.36 | 8.69 | 8.71 | 8.91 | 8.85 |
| 200                 |      |      |      |      |      | 8.04 | 8.13 | 8.06 | 8.43 | 8.06 |      |      |      |      |      |      |
| 190                 |      |      |      |      |      | 8.06 | 8.08 | 8.06 | 8.57 | 8.33 |      |      |      |      |      |      |
| 180                 |      |      |      |      | 7.80 | 8.05 | 8.04 | 8.06 | 8.28 | 8.42 | 8.27 |      |      |      |      |      |
| 170                 |      |      |      | 7.24 | 7.49 | 8.04 | 8.03 | 8.05 | 8.04 | 8.50 | 8.15 | 8.35 |      |      |      |      |
| 160                 |      |      |      | 7.21 | 7.44 | 8.00 | 8.02 | 8.06 | 8.03 | 8.04 | 8.04 | 8.30 | 8.59 |      |      |      |
| 150                 |      |      |      | 7.17 | 7.38 | 7.97 | 8.00 | 8.06 | 8.03 | 8.03 | 8.03 | 8.18 | 8.33 | 8.53 |      |      |
| 140                 |      |      | 7.22 | 7.22 | 7.37 | 7.97 | 7.98 | 8.02 | 8.02 | 8.04 | 8.03 | 8.03 | 8.09 | 8.34 | 8.75 |      |
| 130                 |      |      | 7.28 | 7.25 | 7.45 | 7.95 | 7.97 | 7.97 | 7.98 | 8.05 | 8.04 | 8.03 | 8.01 | 8.28 | 8.56 |      |
| 120                 |      |      | 7.31 | 7.46 | 7.89 | 7.91 | 7.95 | 7.96 | 7.96 | 8.05 | 8.03 | 8.00 | 8.00 | 8.14 | 8.44 | 8.60 |
| 110                 |      | 7.30 | 7.32 | 7.53 | 7.87 | 7.89 | 7.92 | 7.95 | 7.95 | 8.03 | 8.01 | 7.98 | 7.99 | 8.00 | 8.33 | 8.42 |
| 100                 |      | 7.78 | 7.41 | 7.88 | 7.85 | 7.88 | 7.93 | 7.95 | 7.95 | 7.96 | 7.96 | 7.95 | 7.97 | 7.98 | 8.07 | 8.41 |
| 90                  |      | 7.83 | 7.57 | 7.85 | 7.87 | 7.91 | 7.94 | 7.93 | 7.93 | 7.94 | 7.93 | 7.92 | 7.94 | 7.95 | 7.97 | 7.98 |
| 80                  |      | 7.88 | 7.90 | 7.89 | 7.90 | 7.91 | 7.92 | 7.92 | 7.91 | 7.91 | 7.91 | 7.89 | 7.92 | 7.93 | 7.94 | 7.96 |
| 70                  |      | 7.89 | 7.89 | 7.89 | 7.89 | 7.90 | 7.90 | 7.90 | 7.90 | 7.91 | 7.90 | 7.90 | 7.92 | 7.92 | 7.93 | 7.95 |
| 60                  |      | 7.89 | 7.89 | 7.89 | 7.90 | 7.90 | 7.90 | 7.89 | 7.89 | 7.90 | 7.90 | 7.91 | 7.91 | 7.92 | 7.92 | 7.95 |
| 50                  |      | 7.88 | 7.89 | 7.88 | 7.88 | 7.91 | 7.90 | 7.89 | 7.89 | 7.90 | 7.90 | 7.90 | 7.91 | 7.91 | 7.91 | 7.93 |
| 40                  | 7.94 | 7.87 | 7.87 | 7.88 | 7.89 | 7.89 | 7.89 | 7.88 | 7.89 | 7.89 | 7.89 | 7.89 | 7.90 | 7.91 | 7.88 | 7.90 |
| 30                  | 7.91 | 7.88 | 7.88 | 7.87 | 7.88 | 7.88 | 7.88 | 7.88 | 7.89 | 7.88 | 7.89 | 7.89 | 7.90 | 7.91 | 7.88 | 7.89 |
| 20                  | 7.92 | 7.91 | 7.89 | 7.88 | 7.88 | 7.87 | 7.87 | 7.87 | 7.88 | 7.88 | 7.89 | 7.89 | 7.91 | 7.91 | 7.90 | 7.92 |
| 10                  | 7.93 | 7.91 | 7.89 | 7.90 | 7.88 | 7.89 | 7.88 | 7.88 | 7.88 | 7.89 | 7.89 | 7.89 | 7.95 | 7.93 | 7.93 | 7.95 |
| 5                   | 7.98 | 7.92 | 7.90 | 7.91 | 7.90 | 7.89 | 7.89 | 7.88 | 7.89 | 7.89 | 7.90 | 7.89 | 7.97 | 7.96 | 7.98 | 7.97 |
| 2                   | 7.97 | 7.92 | 7.90 | 7.90 | 7.89 | 7.89 | 7.89 | 7.87 | 7.89 | 7.90 | 7.90 | 7.90 |      |      |      |      |

Table 8: Reactant Quantity - Hydrogen

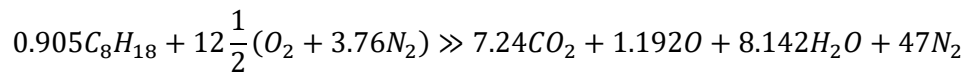
| Reactant Hydrogen (H) | RPM   |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |
|-----------------------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
|                       | 800   | 1000  | 1250  | 1500  | 1750  | 2000  | 2250  | 2500  | 3000  | 3500  | 4000  | 4500  | 5000  | 5500  | 6000  | 6500  |
| FL                    |       | 16.18 | 16.14 | 16.28 | 17.52 | 18.09 | 18.21 | 18.14 | 19.48 | 19.06 | 18.58 | 18.82 | 19.56 | 19.59 | 20.04 | 19.91 |
| 200                   |       |       |       |       |       | 18.09 | 18.29 | 18.12 | 18.97 | 18.14 |       |       |       |       |       |       |
| 190                   |       |       |       |       |       | 18.12 | 18.19 | 18.12 | 19.27 | 18.74 |       |       |       |       |       |       |
| 180                   |       |       |       |       | 17.55 | 18.11 | 18.09 | 18.14 | 18.63 | 18.95 | 18.60 |       |       |       |       |       |
| 170                   |       |       |       | 16.28 | 16.86 | 18.09 | 18.07 | 18.11 | 18.09 | 19.12 | 18.33 | 18.79 |       |       |       |       |
| 160                   |       |       |       | 16.22 | 16.73 | 18.00 | 18.04 | 18.12 | 18.07 | 18.09 | 18.10 | 18.68 | 19.33 |       |       |       |
| 150                   |       |       |       | 16.14 | 16.60 | 17.94 | 18.00 | 18.12 | 18.07 | 18.07 | 18.07 | 18.41 | 18.74 | 19.19 |       |       |
| 140                   |       |       | 16.24 | 16.25 | 16.57 | 17.93 | 17.96 | 18.04 | 18.04 | 18.09 | 18.07 | 18.06 | 18.20 | 18.78 | 19.70 |       |
| 130                   |       |       | 16.39 | 16.31 | 16.76 | 17.88 | 17.94 | 17.94 | 17.95 | 18.11 | 18.09 | 18.06 | 18.01 | 18.63 | 19.26 |       |
| 120                   |       |       | 16.46 | 16.79 | 17.74 | 17.80 | 17.88 | 17.90 | 17.90 | 18.11 | 18.07 | 18.00 | 18.00 | 18.32 | 18.98 | 19.36 |
| 110                   |       | 16.43 | 16.47 | 16.95 | 17.71 | 17.74 | 17.83 | 17.89 | 17.89 | 18.06 | 18.02 | 17.96 | 17.99 | 18.00 | 18.75 | 18.94 |
| 100                   |       | 17.49 | 16.67 | 17.72 | 17.66 | 17.73 | 17.84 | 17.88 | 17.88 | 17.91 | 17.91 | 17.89 | 17.93 | 17.95 | 18.16 | 18.93 |
| 90                    |       | 17.61 | 17.04 | 17.67 | 17.71 | 17.80 | 17.86 | 17.84 | 17.84 | 17.86 | 17.84 | 17.82 | 17.86 | 17.88 | 17.93 | 17.96 |
| 80                    |       | 17.72 | 17.77 | 17.74 | 17.78 | 17.80 | 17.82 | 17.82 | 17.80 | 17.80 | 17.79 | 17.76 | 17.82 | 17.85 | 17.86 | 17.90 |
| 70                    |       | 17.76 | 17.76 | 17.76 | 17.76 | 17.77 | 17.78 | 17.78 | 17.77 | 17.79 | 17.78 | 17.77 | 17.82 | 17.82 | 17.85 | 17.89 |
| 60                    |       | 17.76 | 17.74 | 17.76 | 17.77 | 17.78 | 17.78 | 17.76 | 17.76 | 17.77 | 17.78 | 17.79 | 17.80 | 17.82 | 17.83 | 17.88 |
| 50                    |       | 17.73 | 17.74 | 17.72 | 17.73 | 17.79 | 17.78 | 17.74 | 17.74 | 17.77 | 17.77 | 17.77 | 17.79 | 17.79 | 17.79 | 17.84 |
| 40                    | 17.86 | 17.71 | 17.71 | 17.73 | 17.74 | 17.76 | 17.76 | 17.73 | 17.74 | 17.74 | 17.76 | 17.76 | 17.78 | 17.79 | 17.72 | 17.77 |
| 30                    | 17.79 | 17.72 | 17.72 | 17.71 | 17.72 | 17.73 | 17.72 | 17.72 | 17.74 | 17.73 | 17.76 | 17.74 | 17.78 | 17.79 | 17.72 | 17.76 |
| 20                    | 17.83 | 17.80 | 17.74 | 17.72 | 17.73 | 17.71 | 17.71 | 17.71 | 17.72 | 17.73 | 17.74 | 17.74 | 17.80 | 17.80 | 17.78 | 17.82 |
| 10                    | 17.85 | 17.80 | 17.76 | 17.78 | 17.73 | 17.74 | 17.73 | 17.72 | 17.73 | 17.76 | 17.76 | 17.76 | 17.89 | 17.84 | 17.85 | 17.89 |
| 5                     | 17.95 | 17.83 | 17.78 | 17.79 | 17.77 | 17.76 | 17.74 | 17.73 | 17.74 | 17.76 | 17.77 | 17.76 | 17.93 | 17.91 | 17.95 | 17.93 |
| 2                     | 17.93 | 17.82 | 17.77 | 17.77 | 17.76 | 17.74 | 17.74 | 17.71 | 17.76 | 17.78 | 17.78 | 17.78 |       |       |       |       |

As previously mentioned, when the air:fuel mixture is not stoichiometric it is either rich or lean. Equation 10 shows the reactants and product calculation from full load at 3000RPM when the mixture is rich, the process is the same as when stoichiometric, however as there is now not enough air to allow for complete combustion of the fuel, there is unburnt fuel left over and Carbon Monoxide is created.



*Equation 10: Product & Reactant Calculation when Rich at 3000RPM Full Load*

When the mixture is lean the same calculation is used. A result of this is more air available than is necessary for complete stoichiometric combustion, therefore there is surplus oxygen as a result. An example of this is shown in Equation 11 calculating the products and reactants at 1500 RPM full load.



*Equation 11: Product & Reactant Calculation when Lean at 1500RPM Full Load*

The quantities of reactants at each RPM can be seen below in Table 9, Table 10, Table 11, Table 12 and Table 13. It is worth noting that these calculations do not account for the disassociation of the compounds at the high temperatures associated with combustion. For example, when the AFR is borderline stoichiometric there are high amounts of NO<sub>x</sub> created due to the conditions (Heywood, 1988), other emissions such as hydrocarbons and fine particulate matter are also created. These calculations are out of the scope of this study and so were not further considered.

Table 9: Quantity of Product - Carbon Dioxide

| Product - CO2 | RPM  |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |
|---------------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|
|               | 800  | 1000 | 1250 | 1500 | 1750 | 2000 | 2250 | 2500 | 3000 | 3500 | 4000 | 4500 | 5000 | 5500 | 6000 | 6500 |
| FL            |      | 7.19 | 7.17 | 7.24 | 7.79 | 7.92 | 7.80 | 7.87 | 6.61 | 7.00 | 7.46 | 7.23 | 6.52 | 6.50 | 6.07 | 6.20 |
| 200           |      |      |      |      |      | 7.92 | 7.73 | 7.88 | 7.09 | 7.87 |      |      |      |      |      |      |
| 190           |      |      |      |      |      | 7.88 | 7.82 | 7.88 | 6.80 | 7.31 |      |      |      |      |      |      |
| 180           |      |      |      |      | 7.80 | 7.89 | 7.92 | 7.87 | 7.41 | 7.10 | 7.43 |      |      |      |      |      |
| 170           |      |      |      | 7.24 | 7.49 | 7.92 | 7.93 | 7.89 | 7.92 | 6.94 | 7.69 | 7.25 |      |      |      |      |
| 160           |      |      |      | 7.21 | 7.44 | 8.00 | 7.96 | 7.88 | 7.93 | 7.92 | 7.91 | 7.36 | 6.74 |      |      |      |
| 150           |      |      |      | 7.17 | 7.38 | 7.97 | 8.00 | 7.88 | 7.93 | 7.93 | 7.93 | 7.62 | 7.31 | 6.88 |      |      |
| 140           |      |      | 7.22 | 7.22 | 7.37 | 7.97 | 7.98 | 7.96 | 7.96 | 7.92 | 7.93 | 7.94 | 7.81 | 7.27 | 6.40 |      |
| 130           |      |      | 7.28 | 7.25 | 7.45 | 7.95 | 7.97 | 7.97 | 7.98 | 7.89 | 7.92 | 7.94 | 7.99 | 7.41 | 6.81 |      |
| 120           |      |      | 7.31 | 7.46 | 7.89 | 7.91 | 7.95 | 7.96 | 7.96 | 7.89 | 7.93 | 8.00 | 8.00 | 7.70 | 7.07 | 6.72 |
| 110           |      | 7.30 | 7.32 | 7.53 | 7.87 | 7.89 | 7.92 | 7.95 | 7.95 | 7.94 | 7.98 | 7.98 | 7.99 | 8.00 | 7.29 | 7.11 |
| 100           |      | 7.78 | 7.41 | 7.88 | 7.85 | 7.88 | 7.93 | 7.95 | 7.95 | 7.96 | 7.96 | 7.95 | 7.97 | 7.98 | 7.85 | 7.13 |
| 90            |      | 7.83 | 7.57 | 7.85 | 7.87 | 7.91 | 7.94 | 7.93 | 7.93 | 7.94 | 7.93 | 7.92 | 7.94 | 7.95 | 7.97 | 7.98 |
| 80            |      | 7.88 | 7.90 | 7.89 | 7.90 | 7.91 | 7.92 | 7.92 | 7.91 | 7.91 | 7.91 | 7.89 | 7.92 | 7.93 | 7.94 | 7.96 |
| 70            |      | 7.89 | 7.89 | 7.89 | 7.89 | 7.90 | 7.90 | 7.90 | 7.90 | 7.91 | 7.90 | 7.90 | 7.92 | 7.92 | 7.93 | 7.95 |
| 60            |      | 7.89 | 7.89 | 7.89 | 7.90 | 7.90 | 7.90 | 7.89 | 7.89 | 7.90 | 7.90 | 7.91 | 7.91 | 7.92 | 7.92 | 7.95 |
| 50            |      | 7.88 | 7.89 | 7.88 | 7.88 | 7.91 | 7.90 | 7.89 | 7.89 | 7.90 | 7.90 | 7.90 | 7.91 | 7.91 | 7.91 | 7.93 |
| 40            | 7.94 | 7.87 | 7.87 | 7.88 | 7.89 | 7.89 | 7.89 | 7.88 | 7.89 | 7.89 | 7.89 | 7.89 | 7.90 | 7.91 | 7.88 | 7.90 |
| 30            | 7.91 | 7.88 | 7.88 | 7.87 | 7.88 | 7.88 | 7.88 | 7.88 | 7.89 | 7.88 | 7.89 | 7.89 | 7.90 | 7.91 | 7.88 | 7.89 |
| 20            | 7.92 | 7.91 | 7.89 | 7.88 | 7.88 | 7.87 | 7.87 | 7.87 | 7.88 | 7.88 | 7.89 | 7.89 | 7.91 | 7.91 | 7.90 | 7.92 |
| 10            | 7.93 | 7.91 | 7.89 | 7.90 | 7.88 | 7.89 | 7.88 | 7.88 | 7.88 | 7.89 | 7.89 | 7.89 | 7.95 | 7.93 | 7.93 | 7.95 |
| 5             | 7.98 | 7.92 | 7.90 | 7.91 | 7.90 | 7.89 | 7.89 | 7.88 | 7.89 | 7.89 | 7.90 | 7.89 | 7.97 | 7.96 | 7.98 | 7.97 |
| 2             | 7.97 | 7.92 | 7.90 | 7.90 | 7.89 | 7.89 | 7.89 | 7.87 | 7.89 | 7.90 | 7.90 | 7.90 |      |      |      |      |

Table 10: Quantity of Product - Carbon Monoxide

| Product - CO | RPM   |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |
|--------------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
|              | 800   | 1000  | 1250  | 1500  | 1750  | 2000  | 2250  | 2500  | 3000  | 3500  | 4000  | 4500  | 5000  | 5500  | 6000  | 6500  |
| FL           |       | 0.000 | 0.000 | 0.000 | 0.000 | 0.121 | 0.296 | 0.191 | 2.049 | 1.477 | 0.800 | 1.134 | 2.171 | 2.211 | 2.837 | 2.647 |
| 200          |       |       |       |       |       | 0.121 | 0.402 | 0.173 | 1.343 | 0.191 |       |       |       |       |       |       |
| 190          |       |       |       |       |       | 0.173 | 0.261 | 0.173 | 1.770 | 1.022 |       |       |       |       |       |       |
| 180          |       |       |       |       | 0.000 | 0.156 | 0.121 | 0.191 | 0.873 | 1.323 | 0.836 |       |       |       |       |       |
| 170          |       |       |       | 0.000 | 0.000 | 0.121 | 0.104 | 0.156 | 0.121 | 1.554 | 0.456 | 1.096 |       |       |       |       |
| 160          |       |       |       | 0.000 | 0.000 | 0.000 | 0.052 | 0.173 | 0.104 | 0.121 | 0.139 | 0.947 | 1.849 |       |       |       |
| 150          |       |       |       | 0.000 | 0.000 | 0.000 | 0.000 | 0.173 | 0.104 | 0.104 | 0.104 | 0.563 | 1.022 | 1.652 |       |       |
| 140          |       |       | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.052 | 0.052 | 0.121 | 0.104 | 0.086 | 0.279 | 1.078 | 2.355 |       |
| 130          |       |       | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.156 | 0.121 | 0.086 | 0.017 | 0.873 | 1.750 |       |
| 120          |       |       | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.156 | 0.104 | 0.000 | 0.000 | 0.438 | 1.362 | 1.889 |
| 110          |       | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.086 | 0.034 | 0.000 | 0.000 | 0.000 | 1.040 | 1.304 |
| 100          |       | 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 | 0.226 | 1.285 |
| 90           |       | 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 | 0.000 |
| 80           |       | 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 | 0.000 |
| 70           |       | 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 | 0.000 |
| 60           |       | 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 | 0.000 |
| 50           |       | 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 | 0.000 |
| 40           | 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 | 0.000 | 0.000 |
| 30           | 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 | 0.000 | 0.000 |
| 20           | 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 | 0.000 | 0.000 |
| 10           | 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 | 0.000 | 0.000 |
| 5            | 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 | 0.000 | 0.000 |
| 2            | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |       |       |       |       |

Table 11: Quantity of Product - Water

| Product - H2O | RPM    |        |        |        |        |        |        |        |        |        |        |        |        |        |         |        |
|---------------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|---------|--------|
|               | 800    | 1000   | 1250   | 1500   | 1750   | 2000   | 2250   | 2500   | 3000   | 3500   | 4000   | 4500   | 5000   | 5500   | 6000    | 6500   |
| FL            |        | 8.0916 | 8.0716 | 8.1421 | 8.7587 | 9.0436 | 9.1066 | 9.0687 | 9.7377 | 9.5317 | 9.2878 | 9.4082 | 9.7814 | 9.7961 | 10.0215 | 9.9528 |
| 200           |        |        |        |        |        | 9.0436 | 9.1449 | 9.0624 | 9.4833 | 9.0687 |        |        |        |        |         |        |
| 190           |        |        |        |        |        | 9.0624 | 9.0939 | 9.0624 | 9.6372 | 9.3677 |        |        |        |        |         |        |
| 180           |        |        |        |        | 8.7764 | 9.0561 | 9.0436 | 9.0687 | 9.3143 | 9.4764 | 9.3011 |        |        |        |         |        |
| 170           |        |        |        | 8.1421 | 8.4310 | 9.0436 | 9.0373 | 9.0561 | 9.0436 | 9.5596 | 9.1641 | 9.3947 |        |        |         |        |
| 160           |        |        |        | 8.1117 | 8.3662 | 9.0000 | 9.0186 | 9.0624 | 9.0373 | 9.0436 | 9.0499 | 9.3410 | 9.6657 |        |         |        |
| 150           |        |        |        | 8.0716 | 8.3024 | 8.9691 | 9.0000 | 9.0624 | 9.0373 | 9.0373 | 9.0373 | 9.2028 | 9.3677 | 9.5947 |         |        |
| 140           |        |        | 8.1218 | 8.1269 | 8.2866 | 8.9630 | 8.9814 | 9.0186 | 9.0186 | 9.0436 | 9.0373 | 9.0311 | 9.1003 | 9.3879 | 9.8478  |        |
| 130           |        |        | 8.1931 | 8.1573 | 8.3823 | 8.9384 | 8.9691 | 8.9691 | 8.9753 | 9.0561 | 9.0436 | 9.0311 | 9.0062 | 9.3143 | 9.6301  |        |
| 120           |        |        | 8.2292 | 8.3931 | 8.8717 | 8.9019 | 8.9384 | 8.9507 | 8.9507 | 9.0561 | 9.0373 | 9.0000 | 9.0000 | 9.1577 | 9.4902  | 9.6800 |
| 110           |        | 8.2137 | 8.2344 | 8.4747 | 8.8537 | 8.8717 | 8.9141 | 8.9446 | 8.9446 | 9.0311 | 9.0124 | 8.9814 | 8.9938 | 9.0000 | 9.3745  | 9.4696 |
| 100           |        | 8.7470 | 8.3342 | 8.8597 | 8.8297 | 8.8657 | 8.9201 | 8.9384 | 8.9384 | 8.9568 | 8.9568 | 8.9446 | 8.9630 | 8.9753 | 9.0813  | 9.4627 |
| 90            |        | 8.8059 | 8.5189 | 8.8357 | 8.8537 | 8.9019 | 8.9323 | 8.9201 | 8.9201 | 8.9323 | 8.9201 | 8.9080 | 8.9323 | 8.9384 | 8.9630  | 8.9814 |
| 80            |        | 8.8597 | 8.8838 | 8.8717 | 8.8898 | 8.9019 | 8.9080 | 8.9080 | 8.9019 | 8.9019 | 8.8958 | 8.8777 | 8.9080 | 8.9262 | 8.9323  | 8.9507 |
| 70            |        | 8.8777 | 8.8777 | 8.8777 | 8.8777 | 8.8838 | 8.8898 | 8.8898 | 8.8838 | 8.8958 | 8.8898 | 8.8838 | 8.9080 | 8.9080 | 8.9262  | 8.9446 |
| 60            |        | 8.8777 | 8.8717 | 8.8777 | 8.8838 | 8.8898 | 8.8898 | 8.8777 | 8.8777 | 8.8838 | 8.8898 | 8.8958 | 8.9019 | 8.9080 | 8.9141  | 8.9384 |
| 50            |        | 8.8657 | 8.8717 | 8.8597 | 8.8657 | 8.8958 | 8.8898 | 8.8717 | 8.8717 | 8.8838 | 8.8838 | 8.8838 | 8.8958 | 8.8958 | 8.8958  | 8.9201 |
| 40            | 8.9323 | 8.8537 | 8.8537 | 8.8657 | 8.8717 | 8.8777 | 8.8777 | 8.8657 | 8.8717 | 8.8717 | 8.8777 | 8.8777 | 8.8898 | 8.8958 | 8.8597  | 8.8838 |
| 30            | 8.8958 | 8.8597 | 8.8597 | 8.8537 | 8.8597 | 8.8657 | 8.8597 | 8.8597 | 8.8717 | 8.8657 | 8.8777 | 8.8717 | 8.8898 | 8.8958 | 8.8597  | 8.8777 |
| 20            | 8.9141 | 8.9019 | 8.8717 | 8.8597 | 8.8657 | 8.8537 | 8.8537 | 8.8537 | 8.8597 | 8.8657 | 8.8717 | 8.8717 | 8.9019 | 8.9019 | 8.8898  | 8.9080 |
| 10            | 8.9262 | 8.9019 | 8.8777 | 8.8898 | 8.8657 | 8.8717 | 8.8657 | 8.8597 | 8.8657 | 8.8777 | 8.8777 | 8.8777 | 8.9446 | 8.9201 | 8.9262  | 8.9446 |
| 5             | 8.9753 | 8.9141 | 8.8898 | 8.8958 | 8.8838 | 8.8777 | 8.8717 | 8.8657 | 8.8717 | 8.8777 | 8.8838 | 8.8777 | 8.9630 | 8.9568 | 8.9753  | 8.9630 |
| 2             | 8.9630 | 8.9080 | 8.8838 | 8.8838 | 8.8777 | 8.8717 | 8.8717 | 8.8537 | 8.8777 | 8.8898 | 8.8898 | 8.8898 |        |        |         |        |

Table 12: Quantity of Product - Oxygen

| Product - O2 | RPM   |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |
|--------------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
|              | 800   | 1000  | 1250  | 1500  | 1750  | 2000  | 2250  | 2500  | 3000  | 3500  | 4000  | 4500  | 5000  | 5500  | 6000  | 6500  |
| FL           |       | 1.262 | 1.289 | 1.192 | 0.335 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| 200          |       |       |       |       |       | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |       |       |       |       |       |       |
| 190          |       |       |       |       |       | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |       |       |       |       |       |       |
| 180          |       |       |       |       | 0.311 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |       |       |       |       |       |
| 170          |       |       |       | 1.192 | 0.790 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |       |       |       |       |
| 160          |       |       |       | 1.234 | 0.880 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |       |       |       |
| 150          |       |       |       | 1.289 | 0.969 | 0.043 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |       |       |
| 140          |       |       | 1.220 | 1.213 | 0.991 | 0.051 | 0.026 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |       |
| 130          |       |       | 1.121 | 1.170 | 0.858 | 0.085 | 0.043 | 0.043 | 0.034 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |       |
| 120          |       |       | 1.071 | 0.843 | 0.178 | 0.136 | 0.085 | 0.068 | 0.068 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| 110          |       | 1.092 | 1.063 | 0.730 | 0.203 | 0.178 | 0.119 | 0.077 | 0.077 | 0.000 | 0.000 | 0.026 | 0.009 | 0.000 | 0.000 | 0.000 |
| 100          |       | 0.351 | 0.925 | 0.195 | 0.236 | 0.187 | 0.111 | 0.085 | 0.085 | 0.060 | 0.060 | 0.077 | 0.051 | 0.034 | 0.000 | 0.000 |
| 90           |       | 0.270 | 0.668 | 0.228 | 0.203 | 0.136 | 0.094 | 0.111 | 0.111 | 0.094 | 0.111 | 0.128 | 0.094 | 0.085 | 0.051 | 0.026 |
| 80           |       | 0.195 | 0.161 | 0.178 | 0.153 | 0.136 | 0.128 | 0.128 | 0.136 | 0.136 | 0.145 | 0.170 | 0.128 | 0.102 | 0.094 | 0.068 |
| 70           |       | 0.170 | 0.170 | 0.170 | 0.170 | 0.161 | 0.153 | 0.153 | 0.161 | 0.145 | 0.153 | 0.161 | 0.128 | 0.128 | 0.102 | 0.077 |
| 60           |       | 0.170 | 0.178 | 0.170 | 0.161 | 0.153 | 0.153 | 0.170 | 0.170 | 0.161 | 0.153 | 0.145 | 0.136 | 0.128 | 0.119 | 0.085 |
| 50           |       | 0.187 | 0.178 | 0.195 | 0.187 | 0.145 | 0.153 | 0.178 | 0.178 | 0.161 | 0.161 | 0.161 | 0.145 | 0.145 | 0.145 | 0.111 |
| 40           | 0.094 | 0.203 | 0.203 | 0.187 | 0.178 | 0.170 | 0.170 | 0.187 | 0.178 | 0.178 | 0.170 | 0.170 | 0.153 | 0.145 | 0.195 | 0.161 |
| 30           | 0.145 | 0.195 | 0.195 | 0.203 | 0.195 | 0.187 | 0.195 | 0.195 | 0.178 | 0.187 | 0.170 | 0.178 | 0.153 | 0.145 | 0.195 | 0.170 |
| 20           | 0.119 | 0.136 | 0.178 | 0.195 | 0.187 | 0.203 | 0.203 | 0.203 | 0.195 | 0.187 | 0.178 | 0.178 | 0.136 | 0.136 | 0.153 | 0.128 |
| 10           | 0.102 | 0.136 | 0.170 | 0.153 | 0.187 | 0.178 | 0.187 | 0.195 | 0.187 | 0.170 | 0.170 | 0.170 | 0.077 | 0.111 | 0.102 | 0.077 |
| 5            | 0.034 | 0.119 | 0.153 | 0.145 | 0.161 | 0.170 | 0.178 | 0.187 | 0.178 | 0.170 | 0.161 | 0.170 | 0.051 | 0.060 | 0.034 | 0.051 |
| 2            | 0.051 | 0.128 | 0.161 | 0.161 | 0.170 | 0.178 | 0.178 | 0.203 | 0.170 | 0.153 | 0.153 | 0.153 |       |       |       |       |

Table 13: Quantity of Product - Nitrogen

| Product -<br>N2 | RPM |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |
|-----------------|-----|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|
|                 | 800 | 1000 | 1250 | 1500 | 1750 | 2000 | 2250 | 2500 | 3000 | 3500 | 4000 | 4500 | 5000 | 5500 | 6000 | 6500 |
| FL              |     | 47   | 47   | 47   | 47   | 47   | 47   | 47   | 47   | 47   | 47   | 47   | 47   | 47   | 47   | 47   |
| 200             |     |      |      |      |      | 47   | 47   | 47   | 47   | 47   |      |      |      |      |      |      |
| 190             |     |      |      |      |      | 47   | 47   | 47   | 47   | 47   |      |      |      |      |      |      |
| 180             |     |      |      |      | 47   | 47   | 47   | 47   | 47   | 47   | 47   |      |      |      |      |      |
| 170             |     |      |      | 47   | 47   | 47   | 47   | 47   | 47   | 47   | 47   | 47   |      |      |      |      |
| 160             |     |      |      | 47   | 47   | 47   | 47   | 47   | 47   | 47   | 47   | 47   | 47   |      |      |      |
| 150             |     |      |      | 47   | 47   | 47   | 47   | 47   | 47   | 47   | 47   | 47   | 47   | 47   |      |      |
| 140             |     |      | 47   | 47   | 47   | 47   | 47   | 47   | 47   | 47   | 47   | 47   | 47   | 47   | 47   |      |
| 130             |     |      | 47   | 47   | 47   | 47   | 47   | 47   | 47   | 47   | 47   | 47   | 47   | 47   | 47   |      |
| 120             |     |      | 47   | 47   | 47   | 47   | 47   | 47   | 47   | 47   | 47   | 47   | 47   | 47   | 47   | 47   |
| 110             |     | 47   | 47   | 47   | 47   | 47   | 47   | 47   | 47   | 47   | 47   | 47   | 47   | 47   | 47   | 47   |
| 100             |     | 47   | 47   | 47   | 47   | 47   | 47   | 47   | 47   | 47   | 47   | 47   | 47   | 47   | 47   | 47   |
| 90              |     | 47   | 47   | 47   | 47   | 47   | 47   | 47   | 47   | 47   | 47   | 47   | 47   | 47   | 47   | 47   |
| 80              |     | 47   | 47   | 47   | 47   | 47   | 47   | 47   | 47   | 47   | 47   | 47   | 47   | 47   | 47   | 47   |
| 70              |     | 47   | 47   | 47   | 47   | 47   | 47   | 47   | 47   | 47   | 47   | 47   | 47   | 47   | 47   | 47   |
| 60              |     | 47   | 47   | 47   | 47   | 47   | 47   | 47   | 47   | 47   | 47   | 47   | 47   | 47   | 47   | 47   |
| 50              |     | 47   | 47   | 47   | 47   | 47   | 47   | 47   | 47   | 47   | 47   | 47   | 47   | 47   | 47   | 47   |
| 40              | 47  | 47   | 47   | 47   | 47   | 47   | 47   | 47   | 47   | 47   | 47   | 47   | 47   | 47   | 47   | 47   |
| 30              | 47  | 47   | 47   | 47   | 47   | 47   | 47   | 47   | 47   | 47   | 47   | 47   | 47   | 47   | 47   | 47   |
| 20              | 47  | 47   | 47   | 47   | 47   | 47   | 47   | 47   | 47   | 47   | 47   | 47   | 47   | 47   | 47   | 47   |
| 10              | 47  | 47   | 47   | 47   | 47   | 47   | 47   | 47   | 47   | 47   | 47   | 47   | 47   | 47   | 47   | 47   |
| 5               | 47  | 47   | 47   | 47   | 47   | 47   | 47   | 47   | 47   | 47   | 47   | 47   | 47   | 47   | 47   | 47   |
| 2               | 47  | 47   | 47   | 47   | 47   | 47   | 47   | 47   | 47   | 47   | 47   | 47   |      |      |      |      |

## 1.6 Molecular Weights of the Burned and Unburned Mixture

The molecular weight of the air:fuel mixture is its total mass divided by the number of moles (Taylor, 1985). As the air:fuel blend contains more than one element, the individual molecular weights are combined to give the molecular weight of the mixture. The molecular weight of each element can be found in Appendix: Molecular Thermodynamic Properties (Heywood, 1988). (Turns, 2006) The unburned molecular weight is obtained using the reactant quantities and their molecular weights. Equation 12 shows the calculation used and Table 14 shows the unburned weights at each load and RPM. The molecular weight of the burned mixture is calculated using the weight of the products of combustion previously worked out and the molecular weights of each molecule. The calculation can be seen in Equation 13. The resulting molecular weights of the burned mixture can be seen in Table 15.

$$\mathcal{M}_{Unburned} = \frac{(FER \times \mathcal{M}_{C_8H_{18}}) + 12\frac{1}{2}(\mathcal{M}_{O_2} + (3.76\mathcal{M}_{N_2}))}{FER + 12\frac{1}{2}(1 + 3.76)}$$

Equation 12: Unburned Molecular Weight

$$\mathcal{M}_{burned} = \frac{(Qty_{CO_2} \times \mathcal{M}_{CO_2}) + (Qty_{CO} \times \mathcal{M}_{CO}) + (Qty_{H_2O} \times \mathcal{M}_{H_2O}) + (Qty_{O_2} \times \mathcal{M}_{O_2}) + (Qty_{N_2} \times \mathcal{M}_{N_2})}{Qty_{CO_2} + Qty_{CO} + Qty_{H_2O} + Qty_{O_2} + Qty_{N_2}}$$

Equation 13: Burned Molecular Weight

Table 14: Molecular Weight Unburned

| Molecular Weight<br>Unburned (Kg/Kmol) | RPM    |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |
|----------------------------------------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|
|                                        | 800    | 1000   | 1250   | 1500   | 1750   | 2000   | 2250   | 2500   | 3000   | 3500   | 4000   | 4500   | 5000   | 5500   | 6000   | 6500   |
| FL                                     |        | 30.121 | 30.118 | 30.129 | 30.224 | 30.268 | 30.278 | 30.272 | 30.375 | 30.343 | 30.306 | 30.324 | 30.382 | 30.384 | 30.419 | 30.408 |
| 200                                    |        |        |        |        |        | 30.268 | 30.284 | 30.271 | 30.336 | 30.272 |        |        |        |        |        |        |
| 190                                    |        |        |        |        |        | 30.271 | 30.276 | 30.271 | 30.360 | 30.318 |        |        |        |        |        |        |
| 180                                    |        |        |        |        | 30.227 | 30.270 | 30.268 | 30.272 | 30.310 | 30.335 | 30.308 |        |        |        |        |        |
| 170                                    |        |        |        | 30.129 | 30.174 | 30.268 | 30.267 | 30.270 | 30.268 | 30.348 | 30.287 | 30.322 |        |        |        |        |
| 160                                    |        |        |        | 30.124 | 30.164 | 30.261 | 30.264 | 30.271 | 30.267 | 30.268 | 30.269 | 30.314 | 30.364 |        |        |        |
| 150                                    |        |        |        | 30.118 | 30.154 | 30.257 | 30.261 | 30.271 | 30.267 | 30.267 | 30.267 | 30.293 | 30.318 | 30.353 |        |        |
| 140                                    |        |        | 30.126 | 30.127 | 30.151 | 30.256 | 30.259 | 30.264 | 30.264 | 30.268 | 30.267 | 30.266 | 30.277 | 30.321 | 30.392 |        |
| 130                                    |        |        | 30.137 | 30.131 | 30.166 | 30.252 | 30.257 | 30.257 | 30.258 | 30.270 | 30.288 | 30.286 | 30.262 | 30.310 | 30.358 |        |
| 120                                    |        |        | 30.142 | 30.168 | 30.242 | 30.246 | 30.252 | 30.254 | 30.254 | 30.270 | 30.267 | 30.261 | 30.261 | 30.286 | 30.337 | 30.366 |
| 110                                    |        | 30.140 | 30.143 | 30.180 | 30.239 | 30.242 | 30.248 | 30.253 | 30.253 | 30.266 | 30.263 | 30.259 | 30.260 | 30.261 | 30.319 | 30.334 |
| 100                                    |        | 30.222 | 30.159 | 30.240 | 30.235 | 30.241 | 30.249 | 30.252 | 30.252 | 30.255 | 30.255 | 30.253 | 30.256 | 30.258 | 30.274 | 30.333 |
| 90                                     |        | 30.231 | 30.187 | 30.236 | 30.239 | 30.246 | 30.251 | 30.249 | 30.249 | 30.251 | 30.249 | 30.247 | 30.251 | 30.252 | 30.256 | 30.259 |
| 80                                     |        | 30.240 | 30.243 | 30.242 | 30.244 | 30.246 | 30.247 | 30.247 | 30.246 | 30.246 | 30.245 | 30.243 | 30.247 | 30.250 | 30.251 | 30.254 |
| 70                                     |        | 30.243 | 30.243 | 30.243 | 30.243 | 30.243 | 30.244 | 30.244 | 30.243 | 30.245 | 30.244 | 30.243 | 30.247 | 30.247 | 30.250 | 30.253 |
| 60                                     |        | 30.243 | 30.242 | 30.243 | 30.243 | 30.244 | 30.244 | 30.243 | 30.243 | 30.243 | 30.244 | 30.245 | 30.246 | 30.247 | 30.248 | 30.252 |
| 50                                     |        | 30.241 | 30.242 | 30.240 | 30.241 | 30.245 | 30.244 | 30.242 | 30.242 | 30.243 | 30.243 | 30.243 | 30.245 | 30.245 | 30.245 | 30.249 |
| 40                                     | 30.251 | 30.239 | 30.239 | 30.241 | 30.242 | 30.243 | 30.243 | 30.241 | 30.242 | 30.242 | 30.243 | 30.243 | 30.244 | 30.245 | 30.240 | 30.243 |
| 30                                     | 30.245 | 30.240 | 30.240 | 30.239 | 30.240 | 30.241 | 30.240 | 30.240 | 30.242 | 30.241 | 30.243 | 30.242 | 30.244 | 30.245 | 30.240 | 30.243 |
| 20                                     | 30.248 | 30.246 | 30.242 | 30.240 | 30.241 | 30.239 | 30.239 | 30.239 | 30.240 | 30.241 | 30.242 | 30.242 | 30.246 | 30.246 | 30.244 | 30.247 |
| 10                                     | 30.250 | 30.246 | 30.243 | 30.244 | 30.241 | 30.242 | 30.241 | 30.240 | 30.241 | 30.243 | 30.243 | 30.243 | 30.253 | 30.249 | 30.250 | 30.253 |
| 5                                      | 30.258 | 30.248 | 30.244 | 30.245 | 30.243 | 30.243 | 30.242 | 30.241 | 30.242 | 30.243 | 30.243 | 30.243 | 30.256 | 30.255 | 30.258 | 30.256 |
| 2                                      | 30.256 | 30.247 | 30.243 | 30.243 | 30.243 | 30.242 | 30.242 | 30.239 | 30.243 | 30.244 | 30.244 | 30.244 |        |        |        |        |

Table 15: Molecular Weight Burned

| Molecular Weight<br>Burned (Kg/Kmol) | RPM     |         |         |         |         |         |         |         |         |         |         |         |         |         |         |         |
|--------------------------------------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|
|                                      | 800     | 1000    | 1250    | 1500    | 1750    | 2000    | 2250    | 2500    | 3000    | 3500    | 4000    | 4500    | 5000    | 5500    | 6000    | 6500    |
| FL                                   |         | 28.6299 | 28.6304 | 28.6286 | 28.6130 | 28.5788 | 28.5383 | 28.5626 | 28.1405 | 28.2687 | 28.4225 | 28.3463 | 28.1135 | 28.1044 | 27.9663 | 28.0082 |
| 200                                  |         |         |         |         |         | 28.5788 | 28.5137 | 28.5667 | 28.2991 | 28.5626 |         |         |         |         |         |         |
| 190                                  |         |         |         |         |         | 28.5667 | 28.5464 | 28.5667 | 28.2029 | 28.3719 |         |         |         |         |         |         |
| 180                                  |         |         |         |         | 28.6126 | 28.5707 | 28.5788 | 28.5626 | 28.4057 | 28.3034 | 28.4141 |         |         |         |         |         |
| 170                                  |         |         |         | 28.6286 | 28.6213 | 28.5788 | 28.5828 | 28.5707 | 28.5788 | 28.2513 | 28.5014 | 28.3549 |         |         |         |         |
| 160                                  |         |         |         | 28.6294 | 28.6229 | 28.6069 | 28.5949 | 28.5667 | 28.5828 | 28.5788 | 28.5748 | 28.3888 | 28.1852 |         |         |         |
| 150                                  |         |         |         | 28.6304 | 28.6245 | 28.6077 | 28.6069 | 28.5667 | 28.5828 | 28.5828 | 28.5828 | 28.4767 | 28.3719 | 28.2293 |         |         |
| 140                                  |         |         | 28.6291 | 28.6290 | 28.6249 | 28.6079 | 28.6074 | 28.5949 | 28.5949 | 28.5788 | 28.5828 | 28.5868 | 28.5423 | 28.3591 | 28.0726 |         |
| 130                                  |         |         | 28.6273 | 28.6282 | 28.6225 | 28.6085 | 28.6077 | 28.6077 | 28.6075 | 28.5707 | 28.5788 | 28.5868 | 28.6029 | 28.4057 | 28.2073 |         |
| 120                                  |         |         |         | 28.6264 | 28.6222 | 28.6101 | 28.6094 | 28.6085 | 28.6082 | 28.6082 | 28.5707 | 28.5828 | 28.6069 | 28.6069 | 28.5055 | 28.2948 |
| 110                                  |         | 28.6268 | 28.6263 | 28.6202 | 28.6106 | 28.6101 | 28.6091 | 28.6083 | 28.6083 | 28.5868 | 28.5989 | 28.6074 | 28.6071 | 28.6069 | 28.3677 | 28.3077 |
| 100                                  |         |         | 28.6133 | 28.6237 | 28.6105 | 28.6112 | 28.6103 | 28.6089 | 28.6085 | 28.6085 | 28.6080 | 28.6080 | 28.6083 | 28.6079 | 28.6075 | 28.5545 |
| 90                                   |         |         | 28.6118 | 28.6191 | 28.6111 | 28.6106 | 28.6094 | 28.6086 | 28.6089 | 28.6089 | 28.6086 | 28.6089 | 28.6092 | 28.6086 | 28.6085 | 28.6079 |
| 80                                   |         |         | 28.6105 | 28.6098 | 28.6101 | 28.6097 | 28.6094 | 28.6092 | 28.6092 | 28.6094 | 28.6094 | 28.6095 | 28.6100 | 28.6092 | 28.6088 | 28.6086 |
| 70                                   |         |         | 28.6100 | 28.6100 | 28.6100 | 28.6100 | 28.6098 | 28.6097 | 28.6097 | 28.6098 | 28.6095 | 28.6097 | 28.6098 | 28.6092 | 28.6092 | 28.6088 |
| 60                                   |         |         | 28.6100 | 28.6101 | 28.6100 | 28.6098 | 28.6097 | 28.6097 | 28.6100 | 28.6100 | 28.6098 | 28.6097 | 28.6095 | 28.6094 | 28.6092 | 28.6091 |
| 50                                   |         |         | 28.6103 | 28.6101 | 28.6105 | 28.6103 | 28.6095 | 28.6097 | 28.6101 | 28.6101 | 28.6098 | 28.6098 | 28.6098 | 28.6095 | 28.6095 | 28.6095 |
| 40                                   | 28.6086 | 28.6106 | 28.6106 | 28.6103 | 28.6101 | 28.6100 | 28.6100 | 28.6103 | 28.6101 | 28.6101 | 28.6100 | 28.6100 | 28.6100 | 28.6097 | 28.6095 | 28.6105 |
| 30                                   | 28.6095 | 28.6105 | 28.6105 | 28.6106 | 28.6105 | 28.6103 | 28.6105 | 28.6105 | 28.6101 | 28.6103 | 28.6100 | 28.6101 | 28.6101 | 28.6097 | 28.6095 | 28.6105 |
| 20                                   | 28.6091 | 28.6094 | 28.6101 | 28.6105 | 28.6103 | 28.6106 | 28.6106 | 28.6106 | 28.6105 | 28.6103 | 28.6101 | 28.6101 | 28.6101 | 28.6094 | 28.6094 | 28.6097 |
| 10                                   | 28.6088 | 28.6094 | 28.6100 | 28.6097 | 28.6103 | 28.6101 | 28.6103 | 28.6105 | 28.6103 | 28.6100 | 28.6100 | 28.6100 | 28.6100 | 28.6083 | 28.6089 | 28.6088 |
| 5                                    | 28.6075 | 28.6091 | 28.6097 | 28.6095 | 28.6098 | 28.6100 | 28.6101 | 28.6103 | 28.6101 | 28.6100 | 28.6098 | 28.6100 | 28.6079 | 28.6080 | 28.6075 | 28.6079 |
| 2                                    | 28.6079 | 28.6092 | 28.6098 | 28.6098 | 28.6100 | 28.6101 | 28.6101 | 28.6106 | 28.6100 | 28.6097 | 28.6097 | 28.6097 |         |         |         |         |

## 1.7 Gas Constant of Air:Fuel Mix

The gas constant of a compound is a physical constant. It is dependent of the molecular weight of the compound of interest (Turns, 2006). It can be calculated using Equation 14. The gas constants of the burned and unburned mixtures can be seen in Table 16 and Table 17.

$$R \text{ (J/Kg.K)} = \frac{\tilde{R}}{\mathcal{M}}$$

Equation 14: Gas Constant (Heywood, 1988)

$$\tilde{R} = 8314.3 \text{ J/Kmol.k (Heywood, 1988)}$$

Table 16: R Burned

| R Burned<br>(J/Kg.K) | RPM    |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |
|----------------------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|
|                      | 800    | 1000   | 1250   | 1500   | 1750   | 2000   | 2250   | 2500   | 3000   | 3500   | 4000   | 4500   | 5000   | 5500   | 6000   | 6500   |
| FL                   |        | 0.2904 | 0.2904 | 0.2904 | 0.2906 | 0.2909 | 0.2913 | 0.2911 | 0.2955 | 0.2941 | 0.2925 | 0.2933 | 0.2957 | 0.2958 | 0.2973 | 0.2969 |
| 200                  |        |        |        |        |        | 0.2909 | 0.2916 | 0.2911 | 0.2938 | 0.2911 |        |        |        |        |        |        |
| 190                  |        |        |        |        |        | 0.2911 | 0.2913 | 0.2911 | 0.2948 | 0.2931 |        |        |        |        |        |        |
| 180                  |        |        |        |        | 0.2906 | 0.2910 | 0.2909 | 0.2911 | 0.2927 | 0.2938 | 0.2926 |        |        |        |        |        |
| 170                  |        |        |        | 0.2904 | 0.2905 | 0.2909 | 0.2909 | 0.2910 | 0.2909 | 0.2943 | 0.2917 | 0.2932 |        |        |        |        |
| 160                  |        |        |        | 0.2904 | 0.2905 | 0.2906 | 0.2908 | 0.2911 | 0.2909 | 0.2909 | 0.2910 | 0.2929 | 0.2950 |        |        |        |
| 150                  |        |        |        | 0.2904 | 0.2905 | 0.2906 | 0.2906 | 0.2911 | 0.2909 | 0.2909 | 0.2909 | 0.2920 | 0.2931 | 0.2945 |        |        |
| 140                  |        |        | 0.2904 | 0.2904 | 0.2905 | 0.2906 | 0.2906 | 0.2908 | 0.2908 | 0.2909 | 0.2909 | 0.2908 | 0.2913 | 0.2932 | 0.2962 |        |
| 130                  |        |        | 0.2904 | 0.2904 | 0.2905 | 0.2906 | 0.2906 | 0.2906 | 0.2906 | 0.2910 | 0.2909 | 0.2908 | 0.2907 | 0.2927 | 0.2948 |        |
| 120                  |        |        | 0.2904 | 0.2905 | 0.2906 | 0.2906 | 0.2906 | 0.2906 | 0.2906 | 0.2910 | 0.2909 | 0.2906 | 0.2906 | 0.2917 | 0.2939 | 0.2951 |
| 110                  |        | 0.2904 | 0.2904 | 0.2905 | 0.2906 | 0.2906 | 0.2906 | 0.2906 | 0.2906 | 0.2908 | 0.2907 | 0.2906 | 0.2906 | 0.2906 | 0.2931 | 0.2937 |
| 100                  |        | 0.2906 | 0.2905 | 0.2906 | 0.2906 | 0.2906 | 0.2906 | 0.2906 | 0.2906 | 0.2906 | 0.2906 | 0.2906 | 0.2906 | 0.2906 | 0.2912 | 0.2937 |
| 90                   |        | 0.2906 | 0.2905 | 0.2906 | 0.2906 | 0.2906 | 0.2906 | 0.2906 | 0.2906 | 0.2906 | 0.2906 | 0.2906 | 0.2906 | 0.2906 | 0.2906 | 0.2906 |
| 80                   |        | 0.2906 | 0.2906 | 0.2906 | 0.2906 | 0.2906 | 0.2906 | 0.2906 | 0.2906 | 0.2906 | 0.2906 | 0.2906 | 0.2906 | 0.2906 | 0.2906 | 0.2906 |
| 70                   |        | 0.2906 | 0.2906 | 0.2906 | 0.2906 | 0.2906 | 0.2906 | 0.2906 | 0.2906 | 0.2906 | 0.2906 | 0.2906 | 0.2906 | 0.2906 | 0.2906 | 0.2906 |
| 60                   |        | 0.2906 | 0.2906 | 0.2906 | 0.2906 | 0.2906 | 0.2906 | 0.2906 | 0.2906 | 0.2906 | 0.2906 | 0.2906 | 0.2906 | 0.2906 | 0.2906 | 0.2906 |
| 50                   |        | 0.2906 | 0.2906 | 0.2906 | 0.2906 | 0.2906 | 0.2906 | 0.2906 | 0.2906 | 0.2906 | 0.2906 | 0.2906 | 0.2906 | 0.2906 | 0.2906 | 0.2906 |
| 40                   | 0.2906 | 0.2906 | 0.2906 | 0.2906 | 0.2906 | 0.2906 | 0.2906 | 0.2906 | 0.2906 | 0.2906 | 0.2906 | 0.2906 | 0.2906 | 0.2906 | 0.2906 | 0.2906 |
| 30                   | 0.2906 | 0.2906 | 0.2906 | 0.2906 | 0.2906 | 0.2906 | 0.2906 | 0.2906 | 0.2906 | 0.2906 | 0.2906 | 0.2906 | 0.2906 | 0.2906 | 0.2906 | 0.2906 |
| 20                   | 0.2906 | 0.2906 | 0.2906 | 0.2906 | 0.2906 | 0.2906 | 0.2906 | 0.2906 | 0.2906 | 0.2906 | 0.2906 | 0.2906 | 0.2906 | 0.2906 | 0.2906 | 0.2906 |
| 10                   | 0.2906 | 0.2906 | 0.2906 | 0.2906 | 0.2906 | 0.2906 | 0.2906 | 0.2906 | 0.2906 | 0.2906 | 0.2906 | 0.2906 | 0.2906 | 0.2906 | 0.2906 | 0.2906 |
| 5                    | 0.2906 | 0.2906 | 0.2906 | 0.2906 | 0.2906 | 0.2906 | 0.2906 | 0.2906 | 0.2906 | 0.2906 | 0.2906 | 0.2906 | 0.2906 | 0.2906 | 0.2906 | 0.2906 |
| 2                    | 0.2906 | 0.2906 | 0.2906 | 0.2906 | 0.2906 | 0.2906 | 0.2906 | 0.2906 | 0.2906 | 0.2906 | 0.2906 | 0.2906 |        |        |        |        |

Table 17: R Unburned

| R Unburned<br>(JKg.K) | RPM    |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |
|-----------------------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|
|                       | 800    | 1000   | 1250   | 1500   | 1750   | 2000   | 2250   | 2500   | 3000   | 3500   | 4000   | 4500   | 5000   | 5500   | 6000   | 6500   |
| FL                    |        | 0.2760 | 0.2761 | 0.2760 | 0.2751 | 0.2747 | 0.2746 | 0.2747 | 0.2737 | 0.2740 | 0.2744 | 0.2742 | 0.2737 | 0.2736 | 0.2733 | 0.2734 |
| 200                   |        |        |        |        |        | 0.2747 | 0.2746 | 0.2747 | 0.2741 | 0.2747 |        |        |        |        |        |        |
| 190                   |        |        |        |        |        | 0.2747 | 0.2746 | 0.2747 | 0.2739 | 0.2742 |        |        |        |        |        |        |
| 180                   |        |        |        |        | 0.2751 | 0.2747 | 0.2747 | 0.2747 | 0.2743 | 0.2741 | 0.2743 |        |        |        |        |        |
| 170                   |        |        |        | 0.2760 | 0.2756 | 0.2747 | 0.2747 | 0.2747 | 0.2747 | 0.2740 | 0.2745 | 0.2742 |        |        |        |        |
| 160                   |        |        |        | 0.2760 | 0.2756 | 0.2748 | 0.2747 | 0.2747 | 0.2747 | 0.2747 | 0.2747 | 0.2743 | 0.2738 |        |        |        |
| 150                   |        |        |        | 0.2761 | 0.2757 | 0.2748 | 0.2748 | 0.2747 | 0.2747 | 0.2747 | 0.2747 | 0.2745 | 0.2742 | 0.2739 |        |        |
| 140                   |        |        | 0.2760 | 0.2760 | 0.2758 | 0.2748 | 0.2748 | 0.2747 | 0.2747 | 0.2747 | 0.2747 | 0.2747 | 0.2746 | 0.2742 | 0.2736 |        |
| 130                   |        |        | 0.2759 | 0.2759 | 0.2756 | 0.2748 | 0.2748 | 0.2748 | 0.2748 | 0.2747 | 0.2747 | 0.2747 | 0.2747 | 0.2743 | 0.2739 |        |
| 120                   |        |        | 0.2758 | 0.2756 | 0.2749 | 0.2749 | 0.2748 | 0.2748 | 0.2748 | 0.2747 | 0.2747 | 0.2748 | 0.2748 | 0.2745 | 0.2741 | 0.2738 |
| 110                   |        | 0.2759 | 0.2758 | 0.2755 | 0.2750 | 0.2749 | 0.2749 | 0.2748 | 0.2748 | 0.2747 | 0.2747 | 0.2748 | 0.2748 | 0.2748 | 0.2742 | 0.2741 |
| 100                   |        | 0.2751 | 0.2757 | 0.2750 | 0.2750 | 0.2749 | 0.2749 | 0.2748 | 0.2748 | 0.2748 | 0.2748 | 0.2748 | 0.2748 | 0.2748 | 0.2746 | 0.2741 |
| 90                    |        | 0.2750 | 0.2754 | 0.2750 | 0.2750 | 0.2749 | 0.2748 | 0.2749 | 0.2749 | 0.2748 | 0.2749 | 0.2749 | 0.2748 | 0.2748 | 0.2748 | 0.2748 |
| 80                    |        | 0.2750 | 0.2749 | 0.2749 | 0.2749 | 0.2749 | 0.2749 | 0.2749 | 0.2749 | 0.2749 | 0.2749 | 0.2749 | 0.2749 | 0.2749 | 0.2748 | 0.2748 |
| 70                    |        | 0.2749 | 0.2749 | 0.2749 | 0.2749 | 0.2749 | 0.2749 | 0.2749 | 0.2749 | 0.2749 | 0.2749 | 0.2749 | 0.2749 | 0.2749 | 0.2749 | 0.2748 |
| 60                    |        | 0.2749 | 0.2749 | 0.2749 | 0.2749 | 0.2749 | 0.2749 | 0.2749 | 0.2749 | 0.2749 | 0.2749 | 0.2749 | 0.2749 | 0.2749 | 0.2749 | 0.2748 |
| 50                    |        | 0.2749 | 0.2749 | 0.2750 | 0.2749 | 0.2749 | 0.2749 | 0.2749 | 0.2749 | 0.2749 | 0.2749 | 0.2749 | 0.2749 | 0.2749 | 0.2749 | 0.2749 |
| 40                    | 0.2748 | 0.2750 | 0.2750 | 0.2749 | 0.2749 | 0.2749 | 0.2749 | 0.2749 | 0.2749 | 0.2749 | 0.2749 | 0.2749 | 0.2749 | 0.2749 | 0.2750 | 0.2749 |
| 30                    | 0.2749 | 0.2750 | 0.2750 | 0.2750 | 0.2750 | 0.2749 | 0.2750 | 0.2750 | 0.2750 | 0.2749 | 0.2749 | 0.2749 | 0.2749 | 0.2749 | 0.2750 | 0.2749 |
| 20                    | 0.2749 | 0.2749 | 0.2749 | 0.2750 | 0.2749 | 0.2750 | 0.2750 | 0.2750 | 0.2750 | 0.2749 | 0.2749 | 0.2749 | 0.2749 | 0.2749 | 0.2749 | 0.2749 |
| 10                    | 0.2749 | 0.2749 | 0.2749 | 0.2749 | 0.2749 | 0.2749 | 0.2749 | 0.2750 | 0.2749 | 0.2749 | 0.2749 | 0.2749 | 0.2748 | 0.2749 | 0.2749 | 0.2748 |
| 5                     | 0.2748 | 0.2749 | 0.2749 | 0.2749 | 0.2749 | 0.2749 | 0.2749 | 0.2749 | 0.2749 | 0.2749 | 0.2749 | 0.2749 | 0.2748 | 0.2748 | 0.2748 | 0.2748 |
| 2                     | 0.2748 | 0.2749 | 0.2749 | 0.2749 | 0.2749 | 0.2749 | 0.2749 | 0.2750 | 0.2749 | 0.2749 | 0.2749 | 0.2749 | 0.2749 |        |        |        |

## 1.8 Enthalpy of Formation

The enthalpy of formation of a compound is the increase in enthalpy required to form 1 mole of the compound from its base elements in their standard states at atmospheric pressure and at 298.15K. (Heywood, 1988). Figure 2 is a graphical representation of the enthalpy of formation. As can be seen the base elements remain stable until extra energy is added, once enough energy is added, the element will reach its activation energy required to transition into the compound. This compound will remain stable until enough energy is inputted for it to change form. The enthalpies of formation of each element and compound can be found in Appendix: Molecular Thermodynamic Properties. (Turns, 2006) The method for calculating the enthalpy of formation of the air:fuel mixture can be seen in Equation 15, Equation 16 and Equation 17. The results of the calculations can be seen in Table 18, Table 19 and Table 20.

$$\text{Enthalpy Required (MJ/kmol)} = FER \times EOF \text{ Isooctane}$$

Equation 15: Enthalpy Required (Heywood, 1988)

$$\text{Enthalpy Released (MJ/kmol)} = (Qty \text{ CO}_2 \times EOF \text{ CO}_2) + (Qty \text{ CO} \times EOF \text{ CO}) + (Qty \text{ H}_2\text{O} \times EOF \text{ H}_2\text{O})$$

Equation 16: Enthalpy Released (Heywood, 1988)

$$\text{Net Enthalpy Released (MJ/kmol)} = \text{Enthalpy Required} + \text{Enthalpy Released}$$

Equation 17: Net Enthalpy Released (Heywood, 1988)

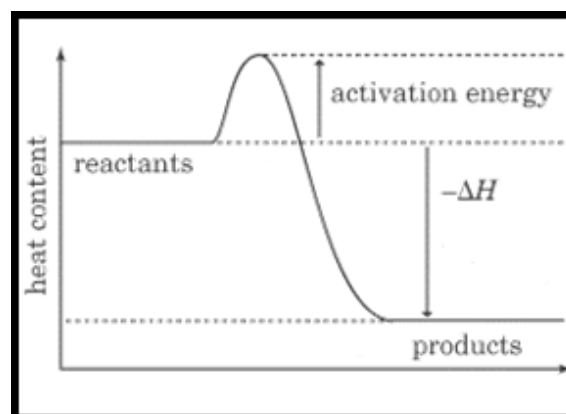


Figure 2: Enthalpy of Formation Diagram (Sparknotes, 2018)

Table 18: Enthalpy Required

| Enthalpy<br>Required<br>(MJ/kmol) | RPM      |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |
|-----------------------------------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|
|                                   | 800      | 1000     | 1250     | 1500     | 1750     | 2000     | 2250     | 2500     | 3000     | 3500     | 4000     | 4500     | 5000     | 5500     | 6000     | 6500     |
| FL                                |          | -201.482 | -200.984 | -202.737 | -218.092 | -225.186 | -226.755 | -225.811 | -242.469 | -237.340 | -231.267 | -234.264 | -243.558 | -243.923 | -249.535 | -247.824 |
| 200                               |          |          |          |          |          | -225.186 | -227.707 | -225.654 | -236.134 | -225.811 |          |          |          |          |          |          |
| 190                               |          |          |          |          |          | -225.654 | -226.439 | -225.654 | -239.965 | -233.257 |          |          |          |          |          |          |
| 180                               |          |          |          |          | -218.531 | -225.498 | -225.186 | -225.811 | -231.927 | -235.963 | -231.597 |          |          |          |          |          |
| 170                               |          |          |          | -202.737 | -209.931 | -225.186 | -225.030 | -225.498 | -225.186 | -238.035 | -228.186 | -233.928 |          |          |          |          |
| 160                               |          |          |          | -201.982 | -208.318 | -224.100 | -224.564 | -225.654 | -225.030 | -225.186 | -225.342 | -232.590 | -240.675 |          |          |          |
| 150                               |          |          |          | -200.984 | -206.730 | -223.331 | -224.100 | -225.654 | -225.030 | -225.030 | -225.030 | -229.150 | -233.257 | -238.908 |          |          |
| 140                               |          |          | -202.233 | -202.359 | -206.337 | -223.178 | -223.638 | -224.564 | -224.564 | -225.186 | -225.030 | -224.874 | -226.597 | -233.759 | -245.210 |          |
| 130                               |          |          | -204.008 | -203.117 | -208.719 | -222.567 | -223.331 | -223.331 | -223.484 | -225.498 | -225.186 | -224.874 | -224.254 | -231.927 | -239.789 |          |
| 120                               |          |          | -204.908 | -208.987 | -220.905 | -221.657 | -222.567 | -222.872 | -222.872 | -225.498 | -225.030 | -224.100 | -224.100 | -228.026 | -236.306 | -241.032 |
| 110                               |          | -204.521 | -205.037 | -211.020 | -220.456 | -220.905 | -221.960 | -222.720 | -222.720 | -224.874 | -224.409 | -223.638 | -223.946 | -224.100 | -233.424 | -235.792 |
| 100                               |          | -217.800 | -207.521 | -220.606 | -219.860 | -220.755 | -222.111 | -222.567 | -222.567 | -223.025 | -223.025 | -222.720 | -223.178 | -223.484 | -226.125 | -235.621 |
| 90                                |          | -219.268 | -212.121 | -220.009 | -220.456 | -221.657 | -222.415 | -222.111 | -222.111 | -222.415 | -222.111 | -221.809 | -222.415 | -222.567 | -223.178 | -223.638 |
| 80                                |          | -220.606 | -221.205 | -220.905 | -221.356 | -221.657 | -221.809 | -221.809 | -221.657 | -221.657 | -221.507 | -221.055 | -221.809 | -222.263 | -222.415 | -222.872 |
| 70                                |          | -221.055 | -221.055 | -221.055 | -221.055 | -221.205 | -221.356 | -221.356 | -221.205 | -221.507 | -221.356 | -221.205 | -221.809 | -221.809 | -222.263 | -222.720 |
| 60                                |          | -221.055 | -220.905 | -221.055 | -221.055 | -221.356 | -221.356 | -221.055 | -221.055 | -221.205 | -221.356 | -221.507 | -221.657 | -221.809 | -221.960 | -222.567 |
| 50                                |          | -220.755 | -220.905 | -220.606 | -220.755 | -221.507 | -221.356 | -220.905 | -220.905 | -221.205 | -221.205 | -221.205 | -221.507 | -221.507 | -221.507 | -222.111 |
| 40                                | -222.415 | -220.456 | -220.456 | -220.755 | -220.905 | -221.055 | -221.055 | -220.755 | -220.905 | -220.905 | -221.055 | -221.055 | -221.356 | -221.507 | -220.606 | -221.205 |
| 30                                | -221.507 | -220.606 | -220.606 | -220.456 | -220.606 | -220.755 | -220.606 | -220.606 | -220.905 | -220.755 | -221.055 | -220.905 | -221.356 | -221.507 | -220.606 | -221.055 |
| 20                                | -221.960 | -221.657 | -220.905 | -220.606 | -220.755 | -220.456 | -220.456 | -220.456 | -220.606 | -220.755 | -220.905 | -220.905 | -221.657 | -221.657 | -221.356 | -221.809 |
| 10                                | -222.263 | -221.657 | -221.055 | -221.356 | -220.755 | -220.905 | -220.755 | -220.606 | -220.755 | -221.055 | -221.055 | -221.055 | -222.720 | -222.111 | -222.263 | -222.720 |
| 5                                 | -223.484 | -221.960 | -221.356 | -221.507 | -221.205 | -221.055 | -220.905 | -220.755 | -220.905 | -221.055 | -221.055 | -221.055 | -223.178 | -223.025 | -223.484 | -223.178 |
| 2                                 | -223.178 | -221.809 | -221.205 | -221.205 | -221.055 | -220.905 | -220.905 | -220.456 | -221.055 | -221.356 | -221.356 | -221.356 |          |          |          |          |

Table 19: Enthalpy Released

| Enthalpy<br>Released<br>(MJ/kmol) | RPM      |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |
|-----------------------------------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|
|                                   | 800      | 1000     | 1250     | 1500     | 1750     | 2000     | 2250     | 2500     | 3000     | 3500     | 4000     | 4500     | 5000     | 5500     | 6000     | 6500     |
| FL                                |          | 4787.222 | 4775.394 | 4817.048 | 5181.879 | 5316.153 | 5303.900 | 5311.272 | 5181.198 | 5221.246 | 5268.664 | 5245.262 | 5172.695 | 5169.844 | 5126.025 | 5139.381 |
| 200                               |          |          |          |          |          | 5316.153 | 5296.466 | 5312.495 | 5230.660 | 5311.272 |          |          |          |          |          |          |
| 190                               |          |          |          |          |          | 5312.495 | 5306.364 | 5312.495 | 5200.745 | 5253.130 |          |          |          |          |          |          |
| 180                               |          |          |          |          | 5192.319 | 5313.716 | 5316.153 | 5311.272 | 5263.516 | 5231.997 | 5266.093 |          |          |          |          |          |
| 170                               |          |          |          | 4817.048 | 4987.976 | 5316.153 | 5317.369 | 5313.716 | 5316.153 | 5215.823 | 5292.725 | 5247.892 |          |          |          |          |
| 160                               |          |          |          | 4799.108 | 4949.656 | 5324.630 | 5321.007 | 5312.495 | 5317.369 | 5316.153 | 5314.935 | 5258.338 | 5195.202 |          |          |          |
| 150                               |          |          |          | 4775.394 | 4911.920 | 5306.357 | 5324.630 | 5312.495 | 5317.369 | 5317.369 | 5317.369 | 5285.196 | 5253.130 | 5209.000 |          |          |
| 140                               |          |          | 4805.073 | 4808.061 | 4902.576 | 5302.718 | 5313.651 | 5321.007 | 5321.007 | 5316.153 | 5317.369 | 5318.583 | 5305.133 | 5249.205 | 5159.797 |          |
| 130                               |          |          | 4847.249 | 4826.069 | 4959.181 | 5288.210 | 5306.357 | 5306.357 | 5310.002 | 5313.716 | 5316.153 | 5318.583 | 5323.424 | 5263.516 | 5202.126 |          |
| 120                               |          |          | 4868.616 | 4965.551 | 5248.719 | 5266.596 | 5288.210 | 5295.454 | 5295.454 | 5313.716 | 5317.369 | 5324.630 | 5324.630 | 5293.974 | 5229.321 | 5192.418 |
| 110                               |          | 4859.436 | 4871.684 | 5013.854 | 5238.051 | 5248.719 | 5273.781 | 5291.829 | 5291.829 | 5318.583 | 5322.216 | 5313.651 | 5320.965 | 5324.630 | 5251.823 | 5233.332 |
| 100                               |          | 5174.942 | 4930.716 | 5241.602 | 5223.894 | 5245.158 | 5277.381 | 5288.210 | 5288.210 | 5299.083 | 5299.083 | 5291.829 | 5302.718 | 5310.002 | 5308.822 | 5234.666 |
| 90                                |          | 5209.813 | 5040.002 | 5227.426 | 5238.051 | 5266.596 | 5284.595 | 5277.381 | 5277.381 | 5284.595 | 5277.381 | 5270.186 | 5284.595 | 5288.210 | 5302.718 | 5313.651 |
| 80                                |          | 5241.602 | 5255.855 | 5248.719 | 5259.430 | 5266.596 | 5270.186 | 5270.186 | 5266.596 | 5266.596 | 5263.011 | 5252.284 | 5270.186 | 5280.985 | 5284.595 | 5295.454 |
| 70                                |          | 5252.284 | 5252.284 | 5252.284 | 5252.284 | 5255.855 | 5259.430 | 5259.430 | 5255.855 | 5263.011 | 5259.430 | 5255.855 | 5270.186 | 5270.186 | 5280.985 | 5291.829 |
| 60                                |          | 5252.284 | 5248.719 | 5252.284 | 5255.855 | 5259.430 | 5259.430 | 5252.284 | 5252.284 | 5255.855 | 5259.430 | 5263.011 | 5266.596 | 5270.186 | 5273.781 | 5288.210 |
| 50                                |          | 5245.158 | 5248.719 | 5241.602 | 5245.158 | 5263.011 | 5259.430 | 5248.719 | 5248.719 | 5255.855 | 5255.855 | 5255.855 | 5263.011 | 5263.011 | 5263.011 | 5277.381 |
| 40                                | 5284.595 | 5238.051 | 5238.051 | 5245.158 | 5248.719 | 5252.284 | 5252.284 | 5245.158 | 5248.719 | 5248.719 | 5252.284 | 5252.284 | 5259.430 | 5263.011 | 5241.602 | 5255.855 |
| 30                                | 5263.011 | 5241.602 | 5241.602 | 5238.051 | 5241.602 | 5245.158 | 5241.602 | 5241.602 | 5248.719 | 5245.158 | 5252.284 | 5248.719 | 5259.430 | 5263.011 | 5241.602 | 5252.284 |
| 20                                | 5273.781 | 5266.596 | 5248.719 | 5241.602 | 5245.158 | 5238.051 | 5238.051 | 5238.051 | 5241.602 | 5245.158 | 5248.719 | 5248.719 | 5266.596 | 5266.596 | 5259.430 | 5270.186 |
| 10                                | 5280.985 | 5266.596 | 5252.284 | 5259.430 | 5245.158 | 5248.719 | 5245.158 | 5241.602 | 5245.158 | 5252.284 | 5252.284 | 5252.284 | 5291.829 | 5277.381 | 5280.985 | 5291.829 |
| 5                                 | 5310.002 | 5273.781 | 5259.430 | 5263.011 | 5255.855 | 5252.284 | 5248.719 | 5245.158 | 5248.719 | 5252.284 | 5255.855 | 5252.284 | 5302.718 | 5299.083 | 5310.002 | 5302.718 |
| 2                                 | 5302.718 | 5270.186 | 5255.855 | 5255.855 | 5252.284 | 5248.719 | 5248.719 | 5238.051 | 5252.284 | 5259.430 | 5259.430 | 5259.430 |          |          |          |          |

Table 20: Net Enthalpy Released

| Net Enthalpy<br>Released<br>(M.J/kmol) | RPM      |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |
|----------------------------------------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|
|                                        | 800      | 1000     | 1250     | 1500     | 1750     | 2000     | 2250     | 2500     | 3000     | 3500     | 4000     | 4500     | 5000     | 5500     | 6000     | 6500     |
| FL                                     |          | 4585.740 | 4574.410 | 4614.311 | 4963.787 | 5090.968 | 5077.145 | 5085.462 | 4938.729 | 4983.906 | 5037.397 | 5010.998 | 4929.137 | 4925.921 | 4876.490 | 4891.557 |
| 200                                    |          |          |          |          |          | 5090.968 | 5068.759 | 5086.841 | 4994.526 | 5085.462 |          |          |          |          |          |          |
| 190                                    |          |          |          |          |          | 5086.841 | 5079.925 | 5086.841 | 4960.780 | 5019.873 |          |          |          |          |          |          |
| 180                                    |          |          |          |          | 4973.787 | 5088.218 | 5090.968 | 5085.462 | 5031.589 | 4996.034 | 5034.497 |          |          |          |          |          |
| 170                                    |          |          |          | 4614.311 | 4778.045 | 5090.968 | 5092.339 | 5088.218 | 5090.968 | 4977.789 | 5064.539 | 5013.965 |          |          |          |          |
| 160                                    |          |          |          | 4597.126 | 4741.338 | 5100.530 | 5096.443 | 5086.841 | 5092.339 | 5090.968 | 5089.594 | 5025.748 | 4954.526 |          |          |          |
| 150                                    |          |          |          | 4574.410 | 4705.190 | 5083.026 | 5100.530 | 5086.841 | 5092.339 | 5092.339 | 5092.339 | 5056.046 | 5019.873 | 4970.091 |          |          |
| 140                                    |          |          | 4602.840 | 4605.702 | 4696.239 | 5079.540 | 5090.013 | 5096.443 | 5096.443 | 5090.968 | 5092.339 | 5093.709 | 5078.536 | 5015.445 | 4914.587 |          |
| 130                                    |          |          | 4643.241 | 4622.952 | 4750.462 | 5065.643 | 5083.026 | 5083.026 | 5086.518 | 5088.218 | 5090.968 | 5093.709 | 5099.170 | 5031.589 | 4962.338 |          |
| 120                                    |          |          | 4663.709 | 4756.564 | 5027.814 | 5044.938 | 5065.643 | 5072.582 | 5072.582 | 5088.218 | 5092.339 | 5100.530 | 5100.530 | 5065.947 | 4993.015 | 4951.386 |
| 110                                    |          | 4654.915 | 4666.647 | 4802.834 | 5017.595 | 5027.814 | 5051.821 | 5069.110 | 5069.110 | 5093.709 | 5097.807 | 5090.013 | 5097.020 | 5100.530 | 5018.399 | 4997.540 |
| 100                                    |          | 4957.142 | 4723.195 | 5020.996 | 5004.033 | 5024.403 | 5055.269 | 5065.643 | 5065.643 | 5076.059 | 5076.059 | 5069.110 | 5079.540 | 5086.518 | 5082.697 | 4999.044 |
| 90                                     |          | 4990.546 | 4827.881 | 5007.417 | 5017.595 | 5044.938 | 5062.180 | 5055.269 | 5055.269 | 5062.180 | 5055.269 | 5048.377 | 5062.180 | 5065.643 | 5079.540 | 5090.013 |
| 80                                     |          | 5020.996 | 5034.650 | 5027.814 | 5038.075 | 5044.938 | 5048.377 | 5048.377 | 5044.938 | 5044.938 | 5041.504 | 5031.229 | 5048.377 | 5058.722 | 5062.180 | 5072.582 |
| 70                                     |          | 5031.229 | 5031.229 | 5031.229 | 5031.229 | 5034.650 | 5038.075 | 5038.075 | 5034.650 | 5041.504 | 5038.075 | 5034.650 | 5048.377 | 5048.377 | 5058.722 | 5069.110 |
| 60                                     |          | 5031.229 | 5027.814 | 5031.229 | 5034.650 | 5038.075 | 5038.075 | 5031.229 | 5031.229 | 5034.650 | 5038.075 | 5041.504 | 5044.938 | 5048.377 | 5051.821 | 5065.643 |
| 50                                     |          | 5024.403 | 5027.814 | 5020.996 | 5024.403 | 5041.504 | 5038.075 | 5027.814 | 5027.814 | 5034.650 | 5034.650 | 5034.650 | 5041.504 | 5041.504 | 5041.504 | 5055.269 |
| 40                                     | 5062.180 | 5017.595 | 5017.595 | 5024.403 | 5027.814 | 5031.229 | 5031.229 | 5024.403 | 5027.814 | 5027.814 | 5031.229 | 5031.229 | 5038.075 | 5041.504 | 5020.996 | 5034.650 |
| 30                                     | 5041.504 | 5020.996 | 5020.996 | 5017.595 | 5020.996 | 5024.403 | 5020.996 | 5020.996 | 5027.814 | 5024.403 | 5031.229 | 5027.814 | 5038.075 | 5041.504 | 5020.996 | 5031.229 |
| 20                                     | 5051.821 | 5044.938 | 5027.814 | 5020.996 | 5024.403 | 5017.595 | 5017.595 | 5017.595 | 5020.996 | 5024.403 | 5027.814 | 5027.814 | 5044.938 | 5044.938 | 5038.075 | 5048.377 |
| 10                                     | 5058.722 | 5044.938 | 5031.229 | 5038.075 | 5024.403 | 5027.814 | 5024.403 | 5020.996 | 5024.403 | 5031.229 | 5031.229 | 5031.229 | 5069.110 | 5055.269 | 5058.722 | 5069.110 |
| 5                                      | 5086.518 | 5051.821 | 5038.075 | 5041.504 | 5034.650 | 5031.229 | 5027.814 | 5024.403 | 5027.814 | 5031.229 | 5034.650 | 5031.229 | 5079.540 | 5076.059 | 5086.518 | 5079.540 |
| 2                                      | 5079.540 | 5048.377 | 5034.650 | 5034.650 | 5031.229 | 5027.814 | 5027.814 | 5017.595 | 5031.229 | 5038.075 | 5038.075 | 5038.075 |          |          |          |          |

## 1.9 Calorific Value

The calorific value of a fuel is its energy content and can be defined as the amount of heat released by the combustion of the fuel at standard conditions. The combustion of the air:fuel mixture leads to the creation of water vapour. The lower calorific value is calculated assuming that none of the water vapour condenses after combustion. The higher calorific value assumes that the water vapour condenses and the heat energy recovered. The higher calorific value tends to be around 11% higher than the lower calorific value due to the extra energy liberated from combustion (Turns, 2006). The higher calorific value was considered for this study, Equation 18 shows how to obtain the results shown in Table 21. As can be seen, the calorific value of the fuel varies at different loads and RPMs due to the different engine requirements, however it is mostly in the region of 44MJ/Kg with a few exceptions. The calorific value of the fuel at different loads is essential in working out the efficiency of the engine as will be discussed later.

$$HCV (MJ/Kg) = \frac{Net\ Enthalpy\ Released}{FER \times Molecular\ Weight\ Isooctane}$$

Equation 18: Higher Calorific Value (Turns, 2006)

Table 21: Calorific Value

| Actual Calorific Value (MJ/Kg) | RPM    |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |
|--------------------------------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|
|                                | 800    | 1000   | 1250   | 1500   | 1750   | 2000   | 2250   | 2500   | 3000   | 3500   | 4000   | 4500   | 5000   | 5500   | 6000   | 6500   |
| FL                             |        | 44.651 | 44.651 | 44.651 | 44.651 | 44.353 | 43.926 | 44.182 | 39.960 | 41.197 | 42.732 | 41.964 | 39.704 | 39.618 | 38.339 | 38.723 |
| 200                            |        |        |        |        |        | 44.353 | 43.670 | 44.225 | 41.495 | 44.182 |        |        |        |        |        |        |
| 190                            |        |        |        |        |        | 44.225 | 44.012 | 44.225 | 40.557 | 42.220 |        |        |        |        |        |        |
| 180                            |        |        |        |        | 44.651 | 44.268 | 44.353 | 44.182 | 42.561 | 41.538 | 42.647 |        |        |        |        |        |
| 170                            |        |        |        | 44.651 | 44.651 | 44.353 | 44.395 | 44.268 | 44.353 | 41.026 | 43.542 | 42.050 |        |        |        |        |
| 160                            |        |        |        | 44.651 | 44.651 | 44.651 | 44.523 | 44.225 | 44.395 | 44.353 | 44.310 | 42.391 | 40.386 |        |        |        |
| 150                            |        |        |        | 44.651 | 44.651 | 44.651 | 44.651 | 44.225 | 44.395 | 44.395 | 44.395 | 43.287 | 42.220 | 40.813 |        |        |
| 140                            |        |        | 44.651 | 44.651 | 44.651 | 44.651 | 44.651 | 44.523 | 44.523 | 44.353 | 44.395 | 44.438 | 43.969 | 42.092 | 39.320 |        |
| 130                            |        |        | 44.651 | 44.651 | 44.651 | 44.651 | 44.651 | 44.651 | 44.651 | 44.268 | 44.353 | 44.438 | 44.609 | 42.561 | 40.599 |        |
| 120                            |        |        | 44.651 | 44.651 | 44.651 | 44.651 | 44.651 | 44.651 | 44.651 | 44.268 | 44.395 | 44.651 | 44.651 | 43.585 | 41.452 | 40.301 |
| 110                            |        | 44.651 | 44.651 | 44.651 | 44.651 | 44.651 | 44.651 | 44.651 | 44.651 | 44.438 | 44.566 | 44.651 | 44.651 | 44.651 | 42.178 | 41.580 |
| 100                            |        | 44.651 | 44.651 | 44.651 | 44.651 | 44.651 | 44.651 | 44.651 | 44.651 | 44.651 | 44.651 | 44.651 | 44.651 | 44.651 | 44.097 | 41.623 |
| 90                             |        | 44.651 | 44.651 | 44.651 | 44.651 | 44.651 | 44.651 | 44.651 | 44.651 | 44.651 | 44.651 | 44.651 | 44.651 | 44.651 | 44.651 | 44.651 |
| 80                             |        | 44.651 | 44.651 | 44.651 | 44.651 | 44.651 | 44.651 | 44.651 | 44.651 | 44.651 | 44.651 | 44.651 | 44.651 | 44.651 | 44.651 | 44.651 |
| 70                             |        | 44.651 | 44.651 | 44.651 | 44.651 | 44.651 | 44.651 | 44.651 | 44.651 | 44.651 | 44.651 | 44.651 | 44.651 | 44.651 | 44.651 | 44.651 |
| 60                             |        | 44.651 | 44.651 | 44.651 | 44.651 | 44.651 | 44.651 | 44.651 | 44.651 | 44.651 | 44.651 | 44.651 | 44.651 | 44.651 | 44.651 | 44.651 |
| 50                             |        | 44.651 | 44.651 | 44.651 | 44.651 | 44.651 | 44.651 | 44.651 | 44.651 | 44.651 | 44.651 | 44.651 | 44.651 | 44.651 | 44.651 | 44.651 |
| 40                             | 44.651 | 44.651 | 44.651 | 44.651 | 44.651 | 44.651 | 44.651 | 44.651 | 44.651 | 44.651 | 44.651 | 44.651 | 44.651 | 44.651 | 44.651 | 44.651 |
| 30                             | 44.651 | 44.651 | 44.651 | 44.651 | 44.651 | 44.651 | 44.651 | 44.651 | 44.651 | 44.651 | 44.651 | 44.651 | 44.651 | 44.651 | 44.651 | 44.651 |
| 20                             | 44.651 | 44.651 | 44.651 | 44.651 | 44.651 | 44.651 | 44.651 | 44.651 | 44.651 | 44.651 | 44.651 | 44.651 | 44.651 | 44.651 | 44.651 | 44.651 |
| 10                             | 44.651 | 44.651 | 44.651 | 44.651 | 44.651 | 44.651 | 44.651 | 44.651 | 44.651 | 44.651 | 44.651 | 44.651 | 44.651 | 44.651 | 44.651 | 44.651 |
| 5                              | 44.651 | 44.651 | 44.651 | 44.651 | 44.651 | 44.651 | 44.651 | 44.651 | 44.651 | 44.651 | 44.651 | 44.651 | 44.651 | 44.651 | 44.651 | 44.651 |
| 2                              | 44.651 | 44.651 | 44.651 | 44.651 | 44.651 | 44.651 | 44.651 | 44.651 | 44.651 | 44.651 | 44.651 | 44.651 |        |        |        |        |

### 1.10 Ideal Gas Law

It is assumed in this study that the air:fuel mixture is an ideal gas and therefore obeys the ideal gas law (Turns, 2006). There are multiple forms of the ideal gas law which are shown below, however the variation used for the purposes of this study is shown in Equation 19.

$$PV = mRT$$

*Equation 19: Ideal Gas Law A (Heywood, 1988)*

$$PV = nRT$$

*Equation 20: Ideal Gas Law B (Heywood, 1988)*

Where P is the pressure, V is the Volume, m is the air:fuel mass in the cylinder, R is the burned gas constant, n is the number of moles and T is the temperature. Equation 19 relates the ideal gas to its weight in Kg, Equation 20 is related to the number of moles of the mixture.

## 2 Pressure Volume Data

This chapter covers the calculation and analysis of the PV diagrams, the work done by the engine and cylinder temperatures from the supplied Ford PV data. It also covers the calculation of the laminar and turbulent flame speeds and mass fraction burned.

### 2.1 Pressure-Volume Diagrams

The pressure-volume data supplied by Ford can be plotted onto a graph and used to calculate the work done by the gas onto the piston. Figure 3 shows an example of a pressure-volume diagram.

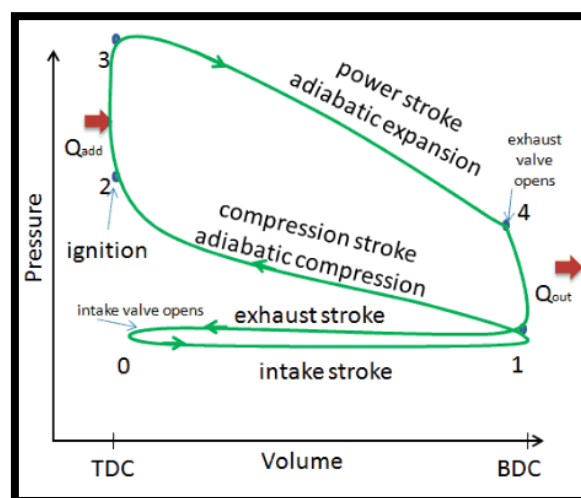


Figure 3:PV Diagram (Nuclear Power, 2018)

The P-V data at different RPMs and loads changes due to the varying demands on the engine. This is illustrated in Figure 4 which is a comparison between the P-Vs at 1000RPM and 6500RPM at full load and further in Figure 5 which compares the differences at different engine loads at 1500RPM. As can be seen from the results in Figure 4 and Figure 5, the diagrams follow the same trend as the example shown in Figure 3. The PV curves at the lower RPMs have 2 clear peaks. The first, smaller peak is where the piston has reached TDC but the combustion has not caught up with it until it has started its downward travel. The combustion catches up with the piston at the beginning of the second and much larger pressure spike. This spike is relatively obvious in turbo-charged engines, particularly at lower engine speeds. Figure 6 shows a comparison between turbocharged engine and naturally aspirated engine. The N/A engine also follows the same trend as the turbocharged engine, however, the time between the piston moving from TDC and combustion catching it up is much less obvious. It is also worth noting that even though the N/A engine has a larger displacement than the turbocharged engine, the graph area is smaller meaning less work is done.

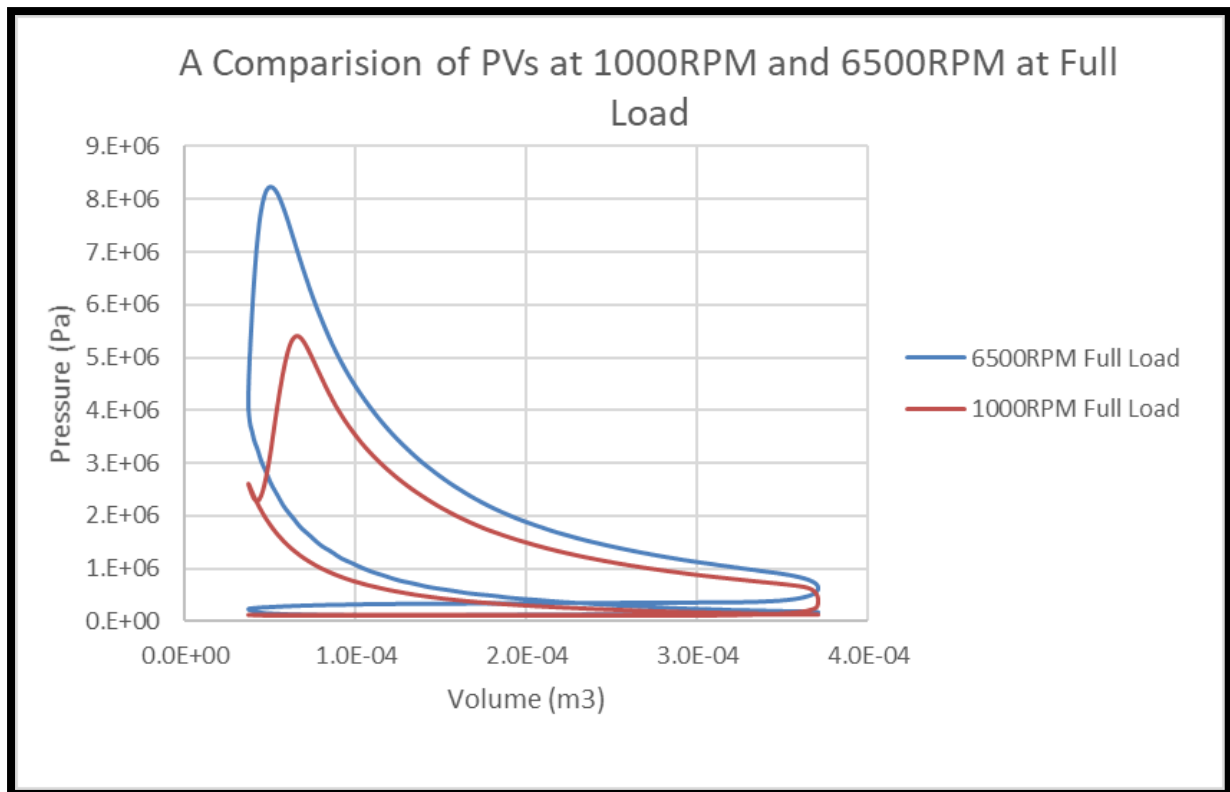


Figure 4: Comparison of PVs at 1000RPM and 6500RPM at Full Load

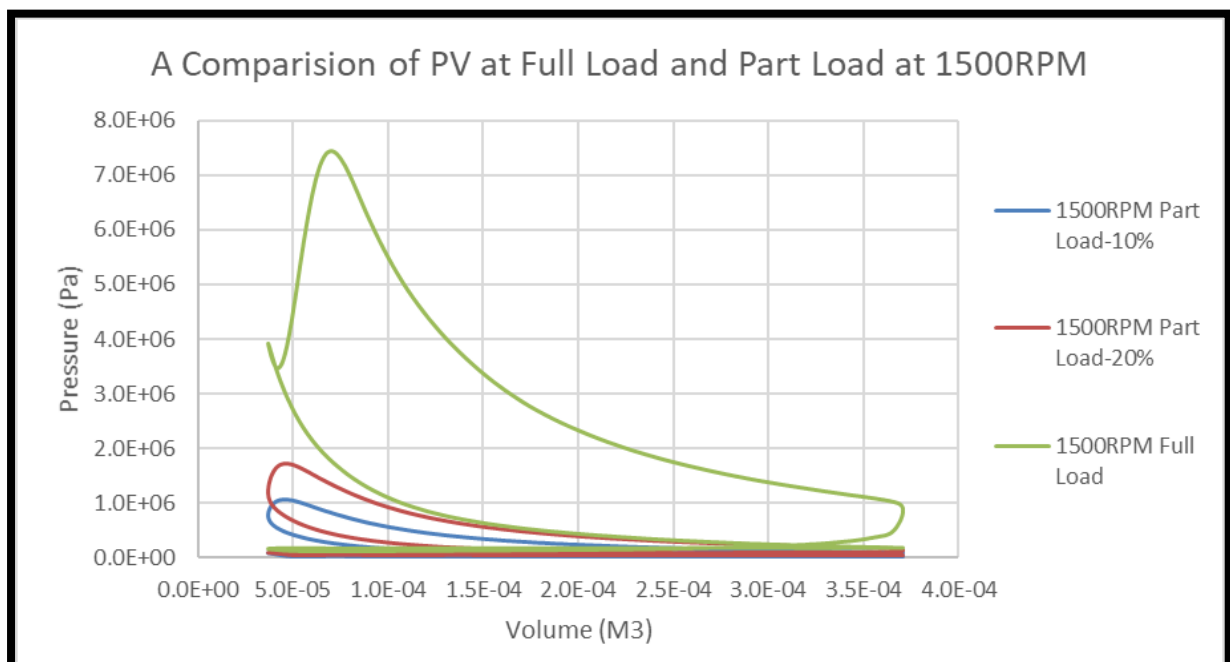


Figure 5: A Comparison of PVs at Full and Part Loads at 1500RPM

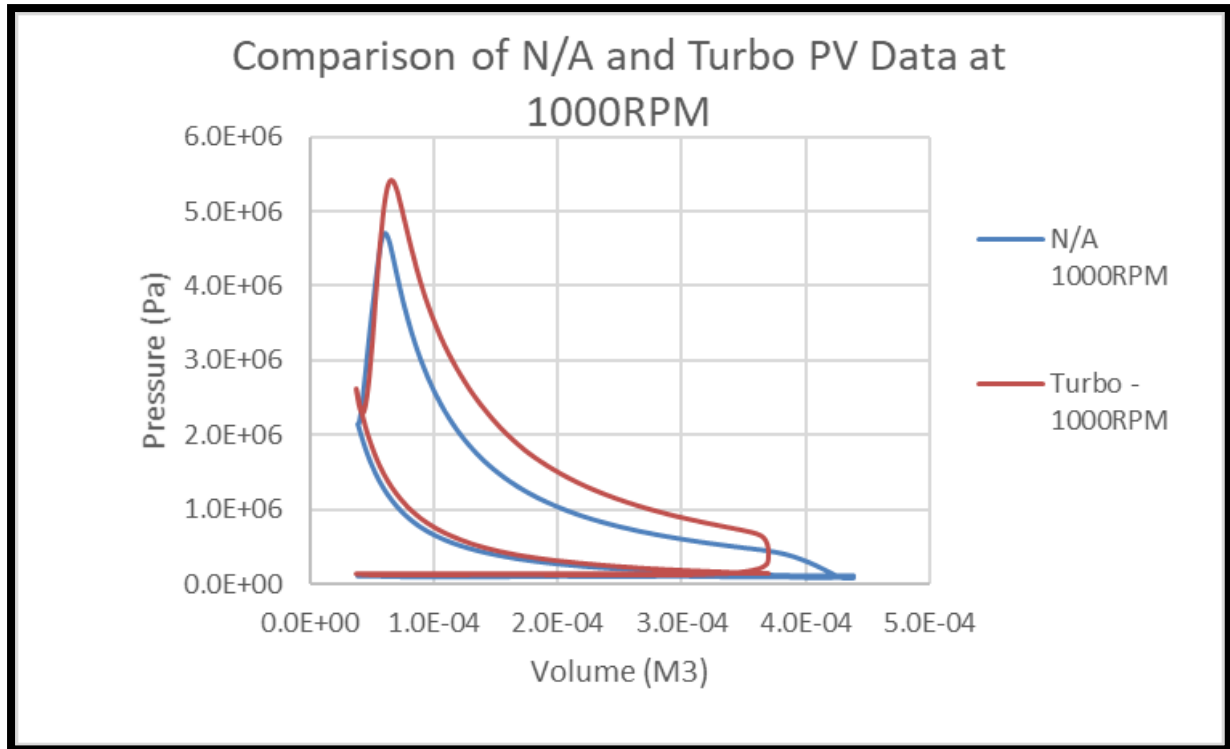


Figure 6: A Comparison of N/A and Turbo PV Data at 1000RPM

## 2.2 Work Done

In thermodynamics, work is defined as the transfer of energy across a system or control volume boundary. There are many types of work, the type of work performed by the engine is compression/expansion work. In this system the cylinder and piston form a boundary. As work is performed by the system, the piston moves down, expanding the system. As the piston returns towards TDC, work is performed on the system as it is compressed (Turns, 2006).

The Ford PV data can be used to calculate the work done by the engine at each degree of crank angle using Equation 21. When the data is represented as a PV diagram, the indicated work for the cycle is obtained by calculating the area of the diagram through integrating around the curve using Equation 22 (Heywood, 1988).

$$\text{Work per Degree} = \left( \frac{P_1 + P_2}{2} \right) \times (V_2 - V_1)$$

Equation 21: Work Done per Degree (Heywood, 1988)

$$W_{c,i} = \oint P dV$$

Equation 22: Net Indicated Work Done (Heywood, 1988)

Table 22: Extract of Work Done per degree data of Ford Fox at Full Load

| Crank Angle | Volume         | Work Done (J) |        |        |        |        |        |
|-------------|----------------|---------------|--------|--------|--------|--------|--------|
|             |                | RPM           |        |        |        |        |        |
| Degrees     | m <sup>3</sup> | 1000          | 2000   | 3000   | 4000   | 5000   | 6000   |
| -10         | 4.03E-05       | -1.622        | -2.969 | -3.222 | -3.079 | -3.012 | -2.738 |
| -9          | 3.97E-05       | -1.487        | -2.722 | -2.955 | -2.825 | -2.763 | -2.512 |
| -8          | 3.92E-05       | -1.367        | -2.504 | -2.719 | -2.601 | -2.542 | -2.308 |
| -7          | 3.87E-05       | -1.216        | -2.227 | -2.419 | -2.314 | -2.261 | -2.051 |
| -6          | 3.82E-05       | -1.082        | -1.983 | -2.154 | -2.061 | -2.012 | -1.829 |
| -5          | 3.79E-05       | -0.916        | -1.680 | -1.826 | -1.748 | -1.706 | -1.553 |
| -4          | 3.76E-05       | -0.771        | -1.414 | -1.537 | -1.471 | -1.436 | -1.306 |
| -3          | 3.74E-05       | -0.596        | -1.093 | -1.188 | -1.137 | -1.110 | -1.009 |
| -2          | 3.72E-05       | -0.417        | -0.764 | -0.831 | -0.796 | -0.776 | -0.707 |
| -1          | 3.71E-05       | -0.261        | -0.479 | -0.521 | -0.499 | -0.487 | -0.445 |
| 0           | 3.71E-05       | -0.105        | -0.192 | -0.209 | -0.200 | -0.195 | -0.179 |
| 1           | 3.71E-05       | 0.104         | 0.192  | 0.209  | 0.200  | 0.195  | 0.179  |
| 2           | 3.72E-05       | 0.260         | 0.478  | 0.520  | 0.500  | 0.488  | 0.451  |
| 3           | 3.74E-05       | 0.414         | 0.761  | 0.828  | 0.797  | 0.778  | 0.727  |
| 4           | 3.76E-05       | 0.590         | 1.086  | 1.181  | 1.142  | 1.115  | 1.052  |
| 5           | 3.79E-05       | 0.762         | 1.403  | 1.527  | 1.484  | 1.450  | 1.384  |
| 6           | 3.82E-05       | 0.904         | 1.664  | 1.814  | 1.775  | 1.734  | 1.679  |
| 7           | 3.87E-05       | 1.039         | 1.915  | 2.092  | 2.066  | 2.018  | 1.991  |
| 8           | 3.92E-05       | 1.193         | 2.200  | 2.412  | 2.408  | 2.352  | 2.367  |
| 9           | 3.97E-05       | 1.341         | 2.471  | 2.724  | 2.756  | 2.692  | 2.764  |
| 10          | 4.03E-05       | 1.460         | 2.688  | 2.984  | 3.064  | 2.991  | 3.142  |

Table 23: Total Work Done- Full Load

| Full Load |               |
|-----------|---------------|
| RPM       | Work Done (J) |
| 1000      | 488.94577     |
| 1250      | 624.94142     |
| 1500      | 742.84077     |
| 1750      | 820.75197     |
| 2000      | 882.50840     |
| 2250      | 895.52627     |
| 2500      | 901.36912     |
| 3000      | 897.48337     |
| 3500      | 904.40024     |
| 4000      | 850.38563     |
| 4500      | 793.84368     |
| 5000      | 757.63067     |
| 5500      | 721.65304     |
| 6000      | 677.18904     |
| 6500      | 597.29185     |

Table 24: Total Work Done - Part Load

| Part Load |          |               |
|-----------|----------|---------------|
| RPM       | Load (%) | Work Done (J) |
| 800       | 5        | 47.03055631   |
| 1500      | 10       | 56.6469384    |
| 1500      | 20       | 112.0114938   |
| 2000      | 30       | 159.875311    |
| 2500      | 20       | 114.2179182   |
| 3000      | 60       | 283.5591532   |
| 4000      | 40       | 218.9153834   |

Table 25: Total Work Done - Naturally Aspirated

| Naturally Aspirated-Full Load |                      |
|-------------------------------|----------------------|
| RPM                           | Sum of Work Done (J) |
| 1000                          | 362.93               |
| 1750                          | 474.11               |
| 2000                          | 499.51               |
| 2500                          | 500.22               |
| 3000                          | 504.99               |
| 3500                          | 507.56               |
| 4000                          | 516.48               |
| 4250                          | 529.03               |
| 4500                          | 526.78               |
| 5000                          | 524.12               |
| 5500                          | 510.85               |
| 6000                          | 495.45               |
| 6500                          | 478.77               |

Table 22 is an extract of the work done per degree calculated from the PV data. It shows how the work changes from negative to positive as the piston moves past TDC and begins the expansion stroke. It also shows that as the RPM increases, as does the work done until 4000RPM where the work done appears to peak and then begins to gradually reduce. Table 23 shows the sum of the work done over the 4-stroke cycle and reinforces further that as the RPM increases as does the work done. The work done peaks at 3500RPM and then begins to reduce as the RPM continues to increase. The total work done at part load can be seen in Table 24 and shows that as load increases, as does the work done. This is particularly obvious at 1500RPM. When comparing the total work done by the ford fox turbocharged engine to that of the naturally aspirated Ford Sigma engine shown in Table 25, the turbocharged engine performs more work. This is due to the turbocharger forcing more air into the cylinder which results in more work.

### 2.3 Cylinder Temperature

Equation 23 shows the ideal gas law rearranged to make temperature the subject. Using the PV data and the molecular weight values previously calculated, it is possible to obtain the temperature at each degree of crank angle.

$$T = \frac{PV}{mR}$$

Equation 23: Temperature from Ideal Gas Law (Heywood, 1988)

The temperature is dependent on the pressure and the volume of the cylinder, and as these change with crank angle, the temperature will also change. It can also be seen that the mass of the air:fuel

mixture changes the temperature. This relationship means that if the AFR is lean, then the temperature will be higher as there is less mass. If the engine is running rich then there is more mass in the cylinder and so the temperature will be lower. It is also because of this relationship that there are errors within the calculations. During the intake stroke the inlet valve is open and the air:fuel mass cannot be accurately measured. This results in unrealistically low temperatures during the intake stroke. An extract of the temperatures calculated from the pressure and volume data can be seen in Table 26.

Table 26: Extract of Temperature data at 6500RPM Full Load

| 6500RPM     |                |                           |                     |
|-------------|----------------|---------------------------|---------------------|
| Crank Angle | Volume         | Average Cylinder Pressure | Average Temperature |
| Degrees     | m <sup>3</sup> | Pascals                   | Kelvin              |
| -10         | 4.03E-05       | 3458300                   | 774.848             |
| -9          | 3.97E-05       | 3538466.7                 | 780.625             |
| -8          | 3.92E-05       | 3615266.7                 | 786.323             |
| -7          | 3.87E-05       | 3669800                   | 788.197             |
| -6          | 3.82E-05       | 3720666.7                 | 790.236             |
| -5          | 3.79E-05       | 3793433.3                 | 798.106             |
| -4          | 3.76E-05       | 3865100                   | 806.744             |
| -3          | 3.74E-05       | 3944466.7                 | 818.271             |
| -2          | 3.72E-05       | 3996900                   | 825.596             |
| -1          | 3.71E-05       | 4082500                   | 841.010             |
| 0           | 3.71E-05       | 4194766.7                 | 863.205             |
| 1           | 3.71E-05       | 4319666.7                 | 889.867             |
| 2           | 3.72E-05       | 4453833.3                 | 919.980             |
| 3           | 3.74E-05       | 4605033.3                 | 955.304             |
| 4           | 3.76E-05       | 4802266.7                 | 1002.354            |
| 5           | 3.79E-05       | 5030433.3                 | 1058.360            |
| 6           | 3.82E-05       | 5265966.7                 | 1118.444            |
| 7           | 3.87E-05       | 5530533.3                 | 1187.536            |
| 8           | 3.92E-05       | 5817433.3                 | 1264.973            |
| 9           | 3.97E-05       | 6129933.3                 | 1351.991            |
| 10          | 4.03E-05       | 6437633.3                 | 1442.024            |

A comparison of temperature at 1000RPM and 6500RPM at full load against crank angle can be seen in Figure 7. The curves show the same trend that as the crankshaft rotates and moves the piston toward TDC the temperature steadily increases. After 0° there is a large spike in temperature as the air:fuel mixture combusts, increasing the pressure and forcing the piston down. The downward travel of the piston causes the volume increase and the pressure to decrease, resulting in the gradual reduction of temperature. The exhaust valve is then opened at around 180°ATDC for 1000RPM and around 70°ATDC for 6500RPM causing the temperature to drop back to pre-combustion temperatures. When comparing the 2 curves it is obvious that at 6500RPM the temperature is higher than at 1000RPM. At higher engine speeds there is less time for heat transfer, whereas at lower RPMs there is longer for heat loss.

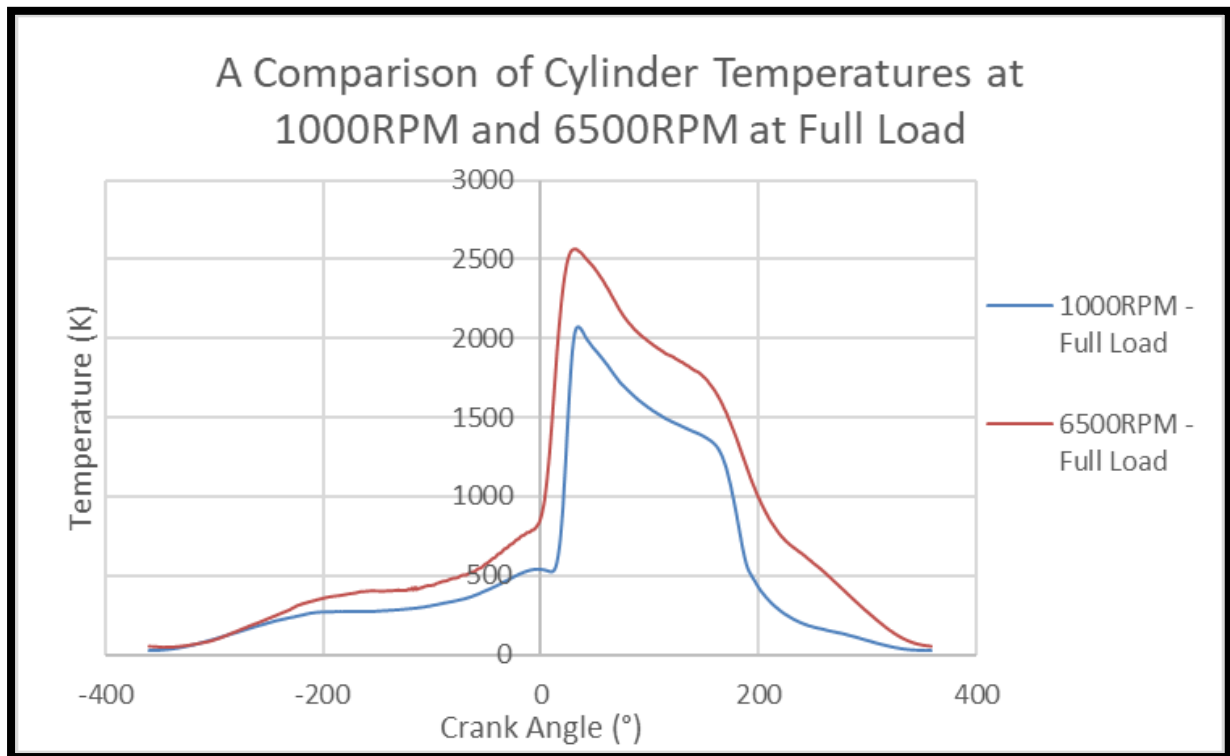


Figure 7: A Comparison of Cylinder Temperatures at 1000RPM and 6500RPM at Full Load

## 2.4 Laminar Flame Speed

The laminar flame speed is the velocity of flame propagation through a homogenous and static air:fuel mixture. It can be calculated using the parameters in Table 27 and Equation 24. The results can be seen in Table 28.

$$S_l = B_m + B_\lambda \left( \frac{1}{\lambda} - \frac{1}{\lambda_m} \right)^2$$

Equation 24: Laminar Flame Speed (Heywood, 1988)

Table 27: Laminar Flame Speed Parameters (Heywood, 1988)

| Fuel      | $\lambda_m$ | $B_m$ | $B_\lambda$ |
|-----------|-------------|-------|-------------|
| Isooctane | 0.88        | 26.3  | -84.7       |

Table 28: Laminar Flame Speed

| Laminar Flame Speed (m/s) | RPM   |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |
|---------------------------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
|                           | 800   | 1000  | 1250  | 1500  | 1750  | 2000  | 2250  | 2500  | 3000  | 3500  | 4000  | 4500  | 5000  | 5500  | 6000  | 6500  |
| FL                        |       | 21.53 | 30.45 | 30.91 | 34.23 | 35.31 | 35.52 | 35.40 | 36.78 | 36.52 | 36.02 | 36.29 | 36.82 | 36.83 | 36.90 | 36.90 |
| 200                       |       |       |       |       |       | 35.31 | 35.63 | 35.38 | 36.44 | 35.40 |       |       |       |       |       |       |
| 190                       |       |       |       |       |       | 35.38 | 35.48 | 35.38 | 36.67 | 36.21 |       |       |       |       |       |       |
| 180                       |       |       |       |       | 34.30 | 35.35 | 35.31 | 35.40 | 36.08 | 36.42 | 36.05 |       |       |       |       |       |
| 170                       |       |       |       | 30.91 | 32.63 | 35.31 | 35.29 | 35.35 | 35.31 | 36.56 | 35.69 | 36.26 |       |       |       |       |
| 160                       |       |       |       | 30.72 | 32.27 | 35.17 | 35.23 | 35.38 | 35.29 | 35.31 | 35.33 | 36.15 | 36.71 |       |       |       |
| 150                       |       |       |       | 30.45 | 31.90 | 35.06 | 35.17 | 35.38 | 35.29 | 35.29 | 35.29 | 35.80 | 36.21 | 36.62 |       |       |
| 140                       |       |       | 30.78 | 30.81 | 31.81 | 35.03 | 35.10 | 35.23 | 35.23 | 35.31 | 35.29 | 35.27 | 35.50 | 36.25 | 36.86 |       |
| 130                       |       |       | 31.24 | 31.01 | 32.36 | 34.95 | 35.06 | 35.06 | 35.08 | 35.35 | 35.31 | 35.27 | 35.19 | 36.08 | 36.66 |       |
| 120                       |       |       | 31.46 | 32.42 | 34.69 | 34.81 | 34.95 | 34.99 | 34.99 | 35.35 | 35.29 | 35.17 | 35.17 | 35.67 | 36.45 | 36.72 |
| 110                       |       | 31.37 | 31.49 | 32.86 | 34.62 | 34.69 | 34.85 | 34.97 | 34.97 | 35.27 | 35.21 | 35.10 | 35.14 | 35.17 | 36.22 | 36.41 |
| 100                       |       | 34.18 | 32.09 | 34.64 | 34.52 | 34.67 | 34.88 | 34.95 | 34.95 | 35.01 | 35.01 | 34.97 | 35.03 | 35.08 | 35.44 | 36.40 |
| 90                        |       | 34.43 | 33.09 | 34.55 | 34.62 | 34.81 | 34.92 | 34.88 | 34.88 | 34.92 | 34.88 | 34.83 | 34.92 | 34.95 | 35.03 | 35.10 |
| 80                        |       | 34.64 | 34.74 | 34.69 | 34.76 | 34.81 | 34.83 | 34.83 | 34.81 | 34.81 | 34.79 | 34.72 | 34.83 | 34.90 | 34.92 | 34.99 |
| 70                        |       | 34.72 | 34.72 | 34.72 | 34.72 | 34.74 | 34.76 | 34.76 | 34.74 | 34.79 | 34.76 | 34.74 | 34.83 | 34.83 | 34.90 | 34.97 |
| 60                        |       | 34.72 | 34.69 | 34.72 | 34.74 | 34.76 | 34.76 | 34.72 | 34.72 | 34.74 | 34.76 | 34.79 | 34.81 | 34.83 | 34.85 | 34.95 |
| 50                        |       | 34.67 | 34.69 | 34.64 | 34.67 | 34.79 | 34.76 | 34.69 | 34.69 | 34.74 | 34.74 | 34.74 | 34.79 | 34.79 | 34.79 | 34.88 |
| 40                        | 34.92 | 34.62 | 34.62 | 34.67 | 34.69 | 34.72 | 34.72 | 34.67 | 34.69 | 34.69 | 34.72 | 34.72 | 34.76 | 34.79 | 34.64 | 34.74 |
| 30                        | 34.79 | 34.64 | 34.64 | 34.62 | 34.64 | 34.67 | 34.64 | 34.64 | 34.69 | 34.67 | 34.72 | 34.69 | 34.76 | 34.79 | 34.64 | 34.72 |
| 20                        | 34.85 | 34.81 | 34.69 | 34.64 | 34.67 | 34.62 | 34.62 | 34.62 | 34.64 | 34.67 | 34.69 | 34.69 | 34.81 | 34.81 | 34.76 | 34.83 |
| 10                        | 34.90 | 34.81 | 34.72 | 34.76 | 34.67 | 34.69 | 34.67 | 34.64 | 34.67 | 34.72 | 34.72 | 34.72 | 34.97 | 34.88 | 34.90 | 34.97 |
| 5                         | 35.08 | 34.85 | 34.76 | 34.79 | 34.74 | 34.72 | 34.69 | 34.67 | 34.69 | 34.72 | 34.74 | 34.72 | 35.03 | 35.01 | 35.08 | 35.03 |
| 2                         | 35.03 | 34.83 | 34.74 | 34.74 | 34.72 | 34.69 | 34.69 | 34.62 | 34.72 | 34.76 | 34.76 | 34.76 |       |       |       |       |

## 2.5 Burn Duration

The burn duration of the combustion process is obtained using the MFB. MFB is used to define the progression of the fuel combusted with relation to crank angle. It is calculated from the PV data and is important in the calculation of various engine parameters (M Mitta, 2008). In this study it will be used to calculate the burn duration and from that the turbulent flame speed using the method described below:

### 2.5.1 Log P Log V

The logs of the PV data are calculated and a log P log V graph plotted, Figure 8 shows an example of the Log P Log V graph at 1000RPM. As can be seen in the expansion and compression slopes of the log P log V graph become linear. From the graph it is possible to estimate where combustion begins and where it finishes. Start of combustion can be identified where the straight line of the compression stroke begins to curve, combustion can be considered to be over when the curve returns to the straight line of the expansion stroke.

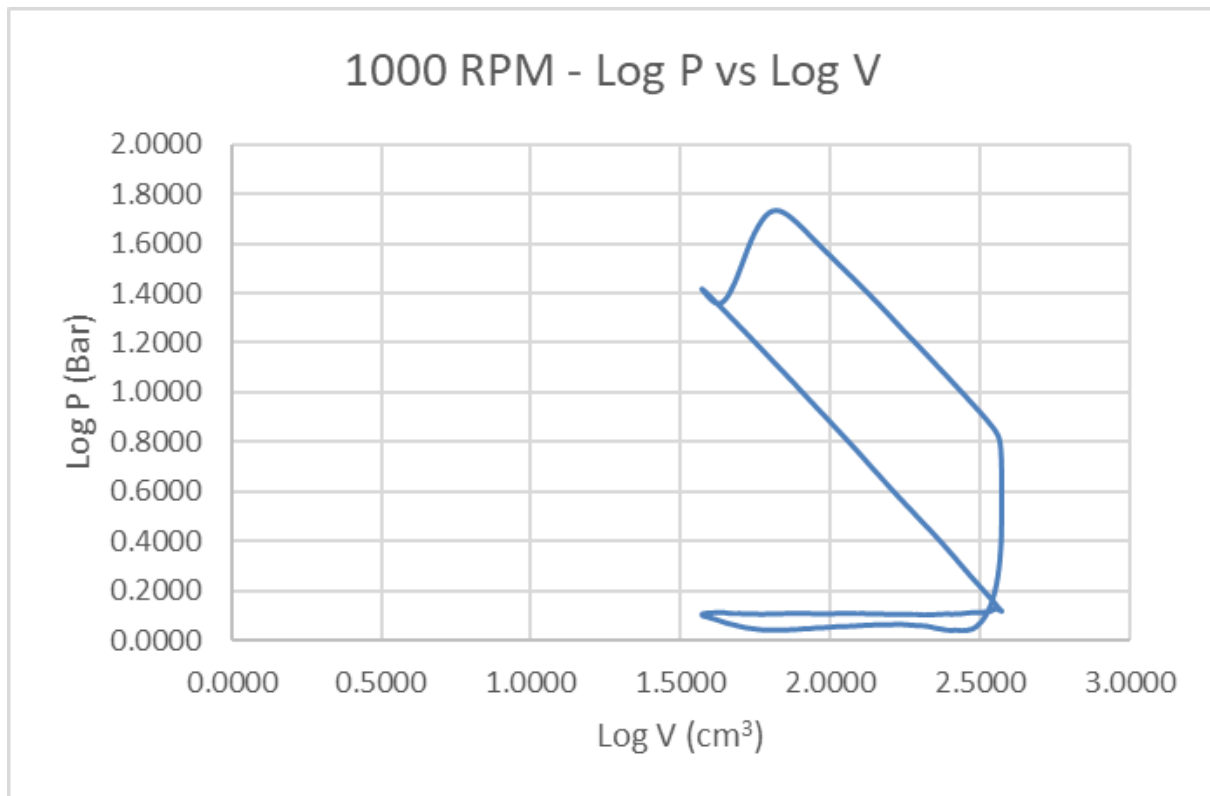


Figure 8: 1000RPM Log P vs Log V Diagram

### 2.5.2 Polytropic Index

The polytropic index of compression and expansion are required to be able to calculate the MFB. The simplest method to do this is to use the gradients of the expansion and compression lines on the Log P Log V graph. The gradients were measured as close to the start and end of combustion as possible. Because of the speculation of the position of the commencement and completion of combustion the polytropic values can only be treated as approximations. More accurate methods of calculating the polytropic index are available, however for the scope of this study these were not considered. The polytropic index values obtained from the gradients can be seen in Table 29 and Table 30.

Table 29: Polytropic Index Full Load

| Polytropic Index |             |           |
|------------------|-------------|-----------|
| RPM              | Compression | Expansion |
| 1000             | 1.26        | 1.19      |
| 1250             | 1.27        | 1.19      |
| 1500             | 1.26        | 1.19      |
| 1750             | 1.27        | 1.20      |
| 2000             | 1.27        | 1.19      |
| 2250             | 1.29        | 1.18      |
| 2500             | 1.27        | 1.19      |
| 3000             | 1.26        | 1.18      |
| 3500             | 1.27        | 1.14      |
| 4000             | 1.25        | 1.12      |
| 4500             | 1.28        | 1.09      |
| 5000             | 1.28        | 1.13      |
| 5500             | 1.27        | 1.09      |
| 6000             | 1.26        | 1.09      |
| 6500             | 1.27        | 1.09      |

Table 30: Polytropic Index Part Load

| Polytropic Index |          |             |           |
|------------------|----------|-------------|-----------|
| RPM              | Load (%) | Compression | Expansion |
| 800.1            | 5        | 1.26        | 1.23      |
| 1500             | 10       | 1.28        | 1.07      |
| 1500             | 20       | 1.28        | 1.03      |
| 2000             | 30       | 1.30        | 1.07      |
| 2500             | 20       | 1.29        | 1.10      |
| 3000             | 60       | 1.29        | 1.18      |
| 4000             | 40       | 1.31        | 1.17      |

### 2.5.3 Extra Pressure from Combustion ( $\Delta P$ )

The extra pressure gained from combustion rather than pressure experience by the gases in the cylinder because of compression and expansion can be calculated for each degree of crank angle and plotted on a graph (Figure 9). In theory, where the pressure begins to rapidly increase to a peak on the graph is where combustion begins and where it levels back off is where combustion finishes. The extra pressure is calculated using Equation 25.

$$\Delta P = ((P_2 - P_1) \times \frac{V_1}{V_2})$$

Equation 25: Delta P (Heywood, 1988)

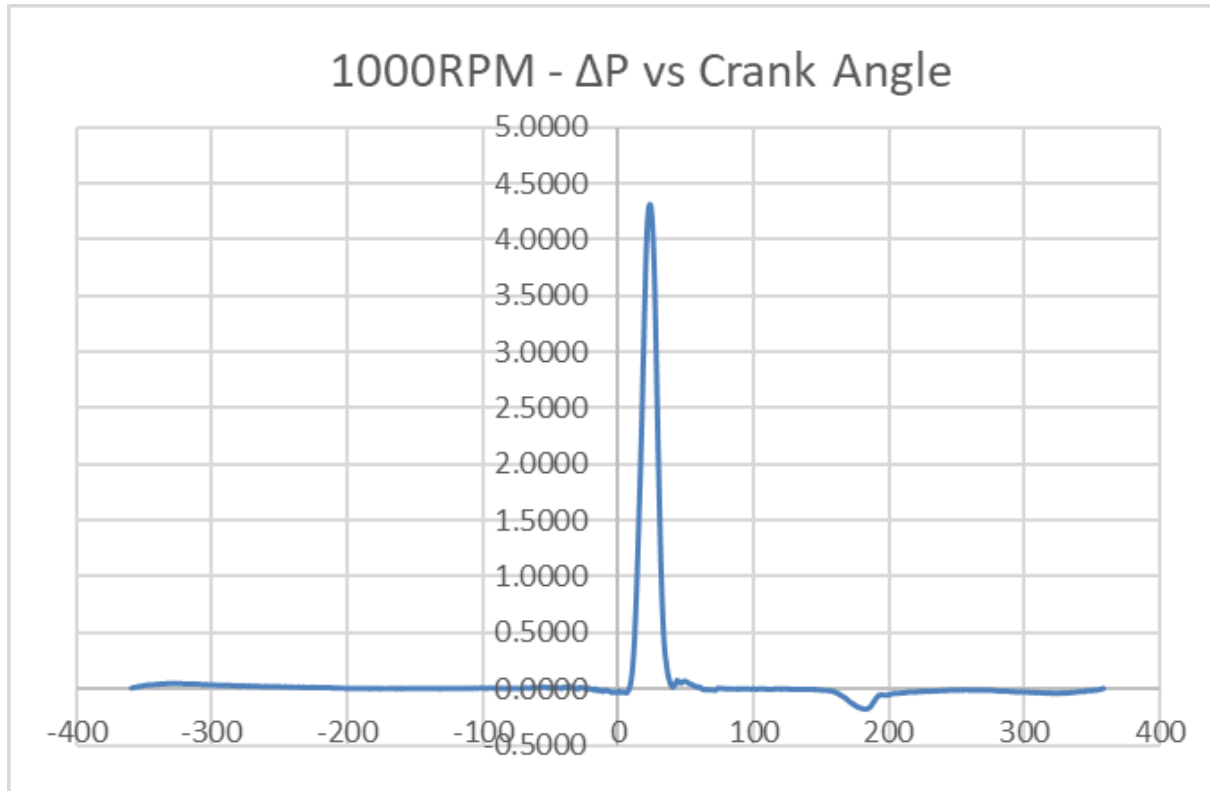


Figure 9: Extra Pressure from Combustion at 1000RPM

#### 2.5.4 Mass Fraction Burn

Using the results from the  $\Delta P$  calculations it is possible to obtain the MFB. This is achieved by calculating the sum of the  $\Delta P$  where the values become stable and positive through until the positive stability is gone and values begin to turn negative again. This in effect is taking the sum of the extra combustion pressure from the start of combustion to the end of combustion. The cumulative value is then used to calculate the MFB using Equation 26.

$$MFB = \frac{\sum \Delta P \text{ per degree}}{\text{Overall } \sum \Delta P}$$

Equation 26: Mass Fraction Burn (Heywood, 1988)

Using values from the calculations at 1000RPM for clarity

$$MFB = 0.7595 = \frac{44.079}{58.038}$$

The MFB is measured on a scale of 0 to 1, therefore if the value of MFB is smaller than 0 or larger than 1 there is an error in the calculations. MFB can be shown in graphical form as shown in Figure 10.

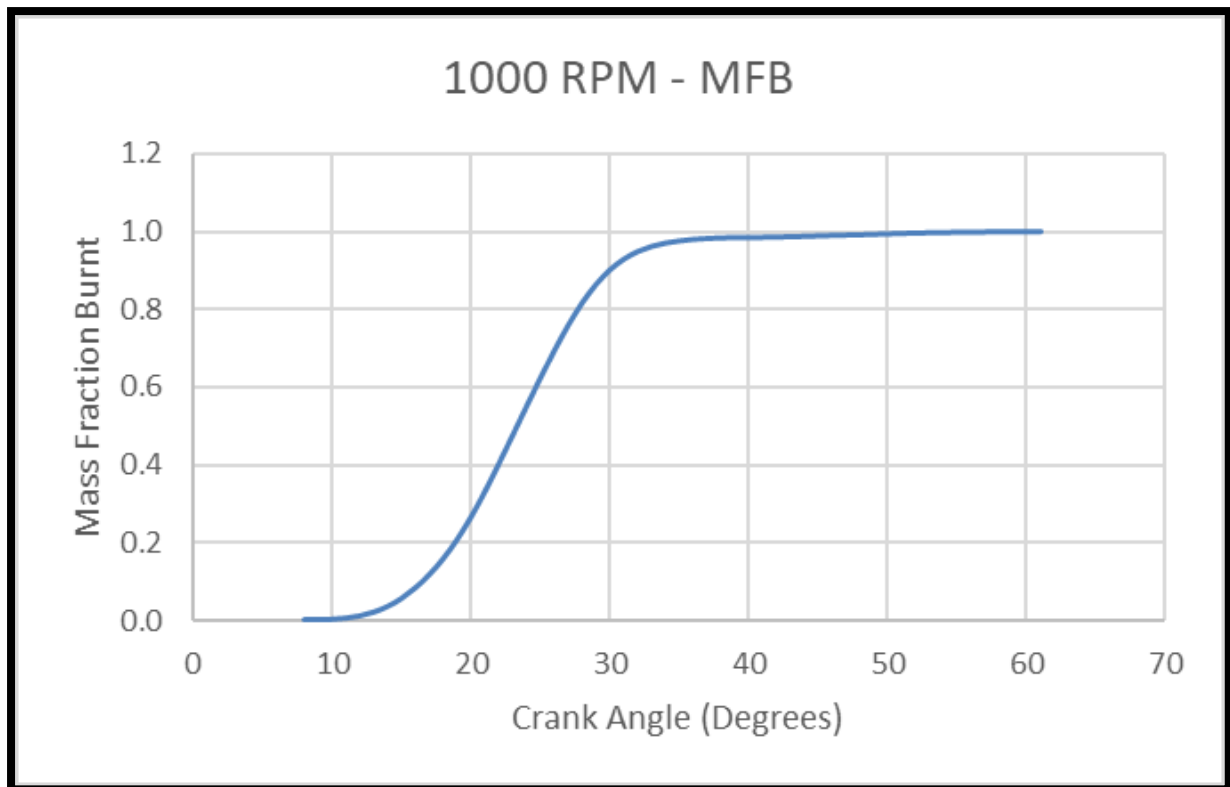


Figure 10: MFB at 1000RPM

#### 2.5.5 Burn Duration

The burn duration is obtained by establishing how many degrees of crank angle the MFB covers. Only the values between 10-90% are considered in the calculations. This is because before 10% the flame is still becoming established and is attributed to the shallow gradient on the MFB graph. After 90% of combustion most of the reactants have been consumed and combustion begins to tail off, this can be seen as the plateau at the top of the curve on the graph. The burn durations in degrees and seconds at full load can be seen in Table 31 and at part load in Table 32.

Table 31: Burn Duration at Full Load

| Burn Duration |         |         |
|---------------|---------|---------|
| RPM           | Degrees | Seconds |
| 1000          | 44      | 0.00733 |
| 1250          | 43      | 0.00573 |
| 1500          | 45      | 0.00500 |
| 1750          | 45      | 0.00429 |
| 2000          | 60      | 0.00500 |
| 2250          | 50      | 0.00370 |
| 2500          | 46      | 0.00307 |
| 3000          | 48      | 0.00267 |
| 3500          | 50      | 0.00238 |
| 4000          | 52      | 0.00217 |
| 4500          | 54      | 0.00200 |
| 5000          | 55      | 0.00183 |
| 5500          | 54      | 0.00164 |
| 6000          | 54      | 0.00150 |
| 6500          | 56      | 0.00144 |

Table 32: Burn Duration at Part Load

| Burn Duration |          |         |         |
|---------------|----------|---------|---------|
| RPM           | Load (%) | Degrees | Seconds |
| 800.1         | 5        | 53      | 0.01104 |
| 1500          | 10       | 81      | 0.00900 |
| 1500          | 20       | 81      | 0.00900 |
| 2000          | 30       | 89      | 0.00742 |
| 2500          | 20       | 92      | 0.00613 |
| 3000          | 60       | 81      | 0.00450 |
| 4000          | 40       | 108     | 0.00450 |

## 2.6 Turbulent Flame Speed

The operating cycles of the engine cause large amounts of turbulence within the cylinder. Turbulence is encouraged within the cylinder as it promotes the combining of the air:fuel mixture. During combustion the flames are exposed to the turbulence, which increases the speed of flame propagation and development. Increasing engine speed can cause the turbulence within the cylinder to rise. Factors such as the air:fuel composition and compression ratio can also affect the flame speed (Heywood, 1988). The Turbulent flame speed can be worked out using Equation 27 .

$$S_t = \frac{D}{\text{Burn Duration}}$$

Equation 27: Turbulent Flame Velocity (Heywood, 1988)

The turbulent flame speeds at full load can be seen in Table 33 and at part load in Table 34 .As can be seen the flame speed increases with RPM and load, this is further reinforced by Figure 11. The graph and tables also show that the turbulent flame speed is much faster than the laminar flame speed.

Table 33: Flame Speeds - Full Load

| <b>RPM</b> | <b>Laminar Flame Speed(m/s)</b> | <b>Turbulent Flame Speed (m/s)</b> |
|------------|---------------------------------|------------------------------------|
| 1000       | 0.22                            | 4.90                               |
| 1250       | 0.30                            | 6.27                               |
| 1500       | 0.31                            | 7.19                               |
| 1750       | 0.34                            | 8.39                               |
| 2000       | 0.35                            | 7.19                               |
| 2250       | 0.36                            | 9.71                               |
| 2500       | 0.35                            | 11.72                              |
| 3000       | 0.37                            | 13.48                              |
| 3500       | 0.37                            | 15.10                              |
| 4000       | 0.36                            | 16.59                              |
| 4500       | 0.36                            | 17.98                              |
| 5000       | 0.37                            | 19.61                              |
| 5500       | 0.37                            | 21.97                              |
| 6000       | 0.37                            | 23.97                              |
| 6500       | 0.37                            | 25.04                              |

Table 34: Flame Speeds - Part Load

| <b>RPM</b> | <b>Load (%)</b> | <b>Laminar Flame Speed(m/s)</b> | <b>Turbulent Flame Speed (m/s)</b> |
|------------|-----------------|---------------------------------|------------------------------------|
| 800.1      | 5               | 0.35                            | 3.26                               |
| 1500       | 10              | 0.35                            | 3.99                               |
| 1500       | 20              | 0.35                            | 3.99                               |
| 2000       | 30              | 0.35                            | 4.85                               |
| 2500       | 20              | 0.35                            | 5.86                               |
| 3000       | 60              | 0.35                            | 7.99                               |
| 4000       | 40              | 0.35                            | 7.99                               |

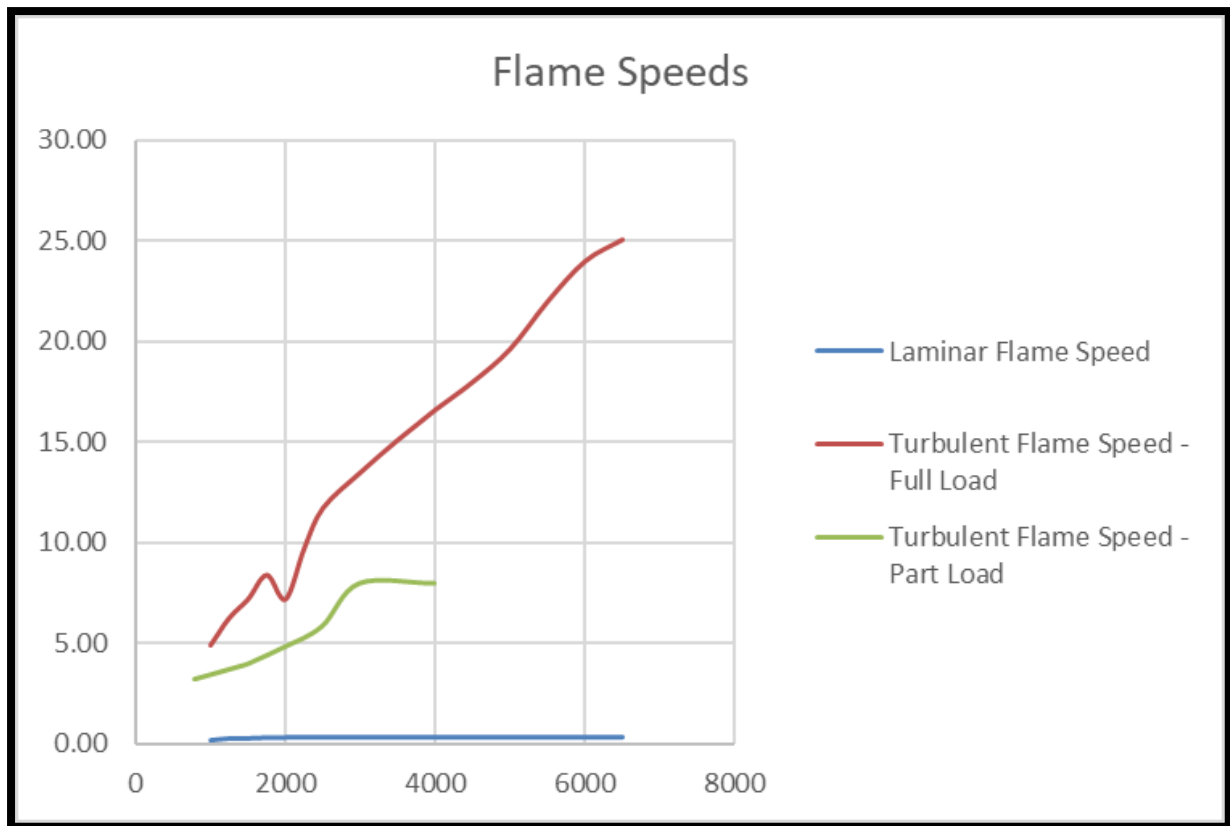


Figure 11: Flame Speeds

### 3 Efficiency Calculations using MEP data

This chapter covers the definition of mean effective pressure. It then goes on to use the supplied BMEP data to calculate values such as the IMEP and FMEP of the engine. The calculated MEP values are then used to obtain the mechanical efficiency and the indicated thermal efficiency. The specific fuel consumption is also discussed and used in the calculation of the fuel conversion efficiency and the energy lost down the exhaust.

#### 3.1 MEP

Mean effective pressure is the constant pressure acting on the piston to produce work during the engine cycle (Lumley, 1999). When comparing engine performance, it is a useful analytical tool as it measures the work done divided by the displaced cylinder volume per cycle. This means that it is not dependant on the size of the engine, whereas characteristics such as torque are (Heywood, 1988). The mean effective pressure is worked out using Equation 28

$$MEP = \frac{p \times n_c}{V_d \times RPM}$$

*Equation 28: Mean Effective Pressure (Heywood, 1988)*

#### 3.2 BMEP

The brake mean effective pressure is the MEP measured at the flywheel. This measurement accounts for engine inefficiencies such as friction, pump losses and other mechanical losses. It measures the ability of the engine to obtain and effectively use a high air flow (Heywood, 1988). Like the MEP, the BMEP is useful for engine performance analysis as it is not affected by the size of the engine. Any variations in the BMEP value is a result of design differences (Lumley, 1999). BMEP can be calculated using Equation 29 which is based on torque, or by using Equation 30 which shows the BMEP calculation using power. The BMEP data for the Ford Fox data was supplied and can be seen in Appendix: Ford Engine Test Data. The units of the data supplied is in kN/m<sup>2</sup>. For the data to be applicable to the study it was necessary to convert the BMEP into bar. The resulting values can be seen in Table 35.

$$BMEP = \frac{4 \times \pi \times \tau}{V_d}$$

*Equation 29: BMEP using Torque (Colin R Ferguson, 2001)*

$$BMEP = \frac{2 \times W_b}{V_d \times RPM}$$

*Equation 30: BMEP using Power (Colin R Ferguson, 2001)*

Table 35: BMEP (Bar)

| BMEP Bar | RPM  |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |
|----------|------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
|          | 800  | 1000  | 1250  | 1500  | 1750  | 2000  | 2250  | 2500  | 3000  | 3500  | 4000  | 4500  | 5000  | 5500  | 6000  | 6500  |
| FL       |      | 13.55 | 17.57 | 21.04 | 23.24 | 24.93 | 25.17 | 25.23 | 25.46 | 25.13 | 23.68 | 22    | 20.85 | 19.66 | 18.43 | 15.87 |
| 200      |      |       |       |       |       | 24.89 | 25.17 | 25.18 | 25.2  | 24.82 |       |       |       |       |       |       |
| 190      |      |       |       |       |       | 23.92 | 23.91 | 23.94 | 23.87 | 23.79 |       |       |       |       |       |       |
| 180      |      |       |       |       | 22.66 | 22.63 | 22.66 | 22.66 | 22.61 | 22.57 | 22.67 |       |       |       |       |       |
| 170      |      |       |       | 21.08 | 21.37 | 21.36 | 21.38 | 21.41 | 21.4  | 21.49 | 21.38 | 21.38 |       |       |       |       |
| 160      |      |       |       | 20.15 | 20.12 | 20.13 | 20.14 | 20.12 | 20.13 | 20.14 | 20.12 | 20.1  | 20.14 |       |       |       |
| 150      |      |       |       | 18.83 | 18.87 | 18.91 | 18.87 | 18.87 | 18.86 | 18.87 | 18.93 | 18.86 | 18.88 | 18.88 |       |       |
| 140      |      |       | 17.54 | 17.56 | 17.61 | 17.71 | 17.59 | 17.61 | 17.59 | 17.62 | 17.52 | 17.62 | 17.62 | 17.6  | 17.61 |       |
| 130      |      |       | 16.34 | 16.38 | 16.35 | 16.36 | 16.36 | 16.35 | 16.35 | 16.36 | 16.38 | 16.36 | 16.36 | 16.35 | 16.37 |       |
| 120      |      |       |       | 15.1  | 15.05 | 15.1  | 15.02 | 15.09 | 15.1  | 15.11 | 15.09 | 15.14 | 15.1  | 15.1  | 15.09 | 15.1  |
| 110      |      |       | 13.46 | 13.84 | 13.86 | 13.83 | 13.84 | 13.84 | 13.85 | 13.84 | 13.77 | 13.84 | 13.85 | 13.84 | 13.85 | 13.84 |
| 100      |      |       | 12.43 | 12.58 | 12.58 | 12.58 | 12.66 | 12.58 | 12.59 | 12.58 | 12.64 | 12.59 | 12.6  | 12.59 | 12.6  | 12.59 |
| 90       |      |       | 11.28 | 11.33 | 11.29 | 11.32 | 11.25 | 11.32 | 11.32 | 11.31 | 11.33 | 11.28 | 11.32 | 11.35 | 11.32 | 11.32 |
| 80       |      |       | 10.04 | 10.07 | 10.09 | 10.06 | 10.09 | 10.07 | 10.07 | 10.06 | 10.06 | 10.06 | 10.06 | 10.08 | 10.08 | 10.06 |
| 70       |      |       | 8.78  | 8.84  | 8.77  | 8.8   | 8.78  | 8.81  | 8.81  | 8.81  | 8.81  | 8.85  | 8.81  | 8.8   | 8.8   | 8.81  |
| 60       |      |       | 7.54  | 7.55  | 7.58  | 7.54  | 7.5   | 7.54  | 7.55  | 7.55  | 7.55  | 7.53  | 7.55  | 7.55  | 7.55  | 7.55  |
| 50       |      |       | 6.27  | 6.29  | 6.28  | 6.29  | 6.3   | 6.29  | 6.29  | 6.3   | 6.29  | 6.27  | 6.29  | 6.29  | 6.29  | 6.28  |
| 40       | 4.73 | 4.94  | 5.03  | 5.06  | 5.02  | 5.03  | 5.03  | 5.03  | 5.02  | 5.03  | 5.04  | 5.03  | 5.03  | 5.05  | 5.03  | 5.02  |
| 30       | 3.93 | 3.68  | 3.76  | 3.74  | 3.77  | 3.75  | 3.78  | 3.77  | 3.77  | 3.79  | 3.77  | 3.77  | 3.77  | 3.78  | 3.78  | 3.78  |
| 20       | 2.51 | 2.36  | 2.5   | 2.42  | 2.51  | 2.51  | 2.51  | 2.5   | 2.52  | 2.52  | 2.52  | 2.51  | 2.51  | 2.52  | 2.53  | 2.51  |
| 10       | 1.35 | 1.09  | 1.2   | 1.21  | 1.26  | 1.22  | 1.22  | 1.21  | 1.32  | 1.25  | 1.25  | 1.21  | 1.25  | 1.3   | 1.34  | 1.35  |
| 5        | 0.71 | 0.52  | 0.59  | 0.58  | 0.74  | 0.64  | 0.6   | 0.62  | 0.55  | 0.62  | 0.63  | 0.62  | 0.61  | 0.71  | 0.66  | 0.69  |
| 2        | 0.26 | 0.32  | 0.12  | 0.25  | 0.23  | 0.29  | 0.26  | 0.26  | 0.28  | 0.25  | 0.25  | 0.26  |       |       |       |       |

### 3.3 IMEP

The IMEP of the engine is the work done on the piston before any losses such as friction and mechanical losses are considered (Stone, 1992) and is calculated using Equation 31. IMEP is shown on a PV diagram in Figure 12. The area within the curve is the indicated work done on the piston by the gases within the cylinder. The IMEP represents the work output per cylinder displacement (Stone, 1992). This means that like the other MEPs, the IMEP can be considered independent of engine size when using to analyse engine performance. The IMEPs of the engine at full load can be seen in Table 36, the IMEP at part load can be seen in Table 37. When comparing the IMEP to the BMEP, the values of IMEP are higher. This is because the BMEP considers the frictional and mechanical losses making it a more realistic value when considering the performance of the engine.

$$IMEP = \frac{\text{Total Work Done}}{\text{Cylinder Displacement}}$$

Equation 31: IMEP (Stone, 1992)

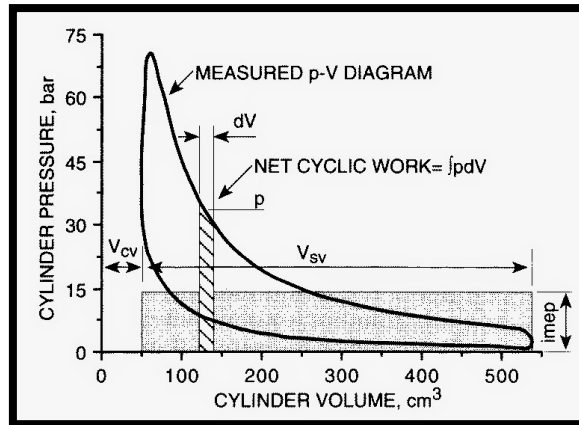


Figure 12: IMEP shown on PV Diagram (Rodgers, 2014)

Table 36: IMEP-Full Load

| RPM  | IMEP - Full Load |
|------|------------------|
|      | Bar              |
| 1000 | 14.68305622      |
| 1250 | 18.76700953      |
| 1500 | 22.30753064      |
| 1750 | 24.64720622      |
| 2000 | 26.50175374      |
| 2250 | 26.89268073      |
| 2500 | 27.06814182      |
| 3000 | 26.95145255      |
| 3500 | 27.15916646      |
| 4000 | 25.53710597      |
| 4500 | 23.83914951      |
| 5000 | 22.75167186      |
| 5500 | 21.67126254      |
| 6000 | 20.33600724      |
| 6500 | 17.93669229      |

Table 37: IMEP-Part Load

| RPM  | Load | IMEP - Full Load |
|------|------|------------------|
|      |      | Bar              |
| 800  | 5    | 1.412329018      |
| 1500 | 10   | 1.701109261      |
| 1500 | 20   | 3.363708522      |
| 2000 | 30   | 4.801060391      |
| 2500 | 20   | 3.429967513      |
| 3000 | 60   | 8.515289886      |
| 4000 | 30   | 6.574035536      |

### 3.4 FMEP

The FMEP of the engine represents the portion of work that is lost in between the piston and the flywheel from factors such as powering oil pumps and friction, this is further illustrated in Figure 13. The FMEP is the difference between the IMEP and BMEP and is calculated using Equation 32. The results of the FMEP can be seen in Table 38 for full load and Table 39 for part load.

$$FMEP = IMEP - BMEP$$

Equation 32: FMEP (X-Engine, 2018)

Table 38: FMEP-Full Load

| RPM  | FMEP - Full Load |
|------|------------------|
|      | Bar              |
| 1000 | 1.133056216      |
| 1250 | 1.197009535      |
| 1500 | 1.267530636      |
| 1750 | 1.407206221      |
| 2000 | 1.571753739      |
| 2250 | 1.722680726      |
| 2500 | 1.838141822      |
| 3000 | 1.491452553      |
| 3500 | 2.029166461      |
| 4000 | 1.857105971      |
| 4500 | 1.839149515      |
| 5000 | 1.901671857      |
| 5500 | 2.011262543      |
| 6000 | 1.906007242      |
| 6500 | 2.066692292      |

Table 39: FMEP - Part Load

| RPM  | Load | FMEP - Full Load |
|------|------|------------------|
|      |      | Bar              |
| 800  | 5    | 0.702329018      |
| 1500 | 10   | 0.491109261      |
| 1500 | 20   | 0.943708522      |
| 2000 | 30   | 1.051060391      |
| 2500 | 20   | 0.929967513      |
| 3000 | 60   | 0.965289886      |
| 4000 | 30   | 2.804035536      |

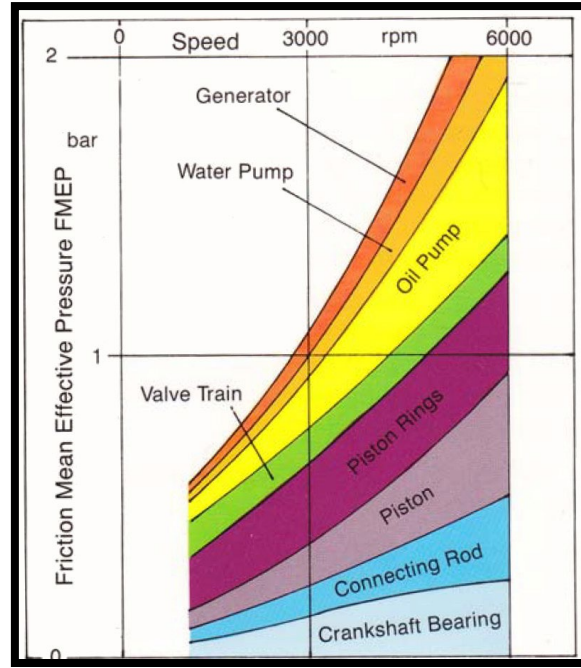


Figure 13: Example of Friction of components in engine (X-Engineer, 2018)

### 3.5 Mechanical Efficiency

The mechanical efficiency of the engine is how effectively it converts the indicated power into brake power (Stone, 1992). It is obtained using Equation 33 and Equation 34.

$$\eta_m = \frac{BMEP}{IMEP}$$

Equation 33: Mechanical Efficiency using BMEP (X-Engineer, 2018)

or

$$\eta_m = 1 - \frac{FMEP}{IMEP}$$

Equation 34: Mechanical Efficiency using FMEP (X-Engineer, 2018)

The mechanical efficiency of the engine at full load can be seen in Table 40. As can be seen there is very little difference in the mechanical at full load from 1500RPM to 3000RPM. However, at 3500RPM the efficiency begins to reduce until 88% at 6500RPM. Looking at the mechanical efficiency at part load shown in Table 41 it becomes clear that the mechanical efficiency is affected by the load of the engine. Comparing the part load results to the full load results at 3000RPM it is possible to see that there is only a small difference in efficiency from 60% to 100%, and the efficiency at 3000RPM 60% load is greater than that at 6500RPM full load suggests that the load of optimum mechanical efficiency is not necessarily full load. When considering Equation 34, the dependence of the mechanical

efficiency of friction can be seen, this is important as at higher RPMs and loads there is more friction created.

*Table 40: Mechanical Efficiency - Full Load*

| <b>RPM</b>  | <b>Mechanical Efficiency-<br/>Full Load (%)</b> |
|-------------|-------------------------------------------------|
| <b>1000</b> | 92.28                                           |
| <b>1250</b> | 93.62                                           |
| <b>1500</b> | 94.32                                           |
| <b>1750</b> | 94.29                                           |
| <b>2000</b> | 94.07                                           |
| <b>2250</b> | 93.59                                           |
| <b>2500</b> | 93.21                                           |
| <b>3000</b> | 94.47                                           |
| <b>3500</b> | 92.53                                           |
| <b>4000</b> | 92.73                                           |
| <b>4500</b> | 92.29                                           |
| <b>5000</b> | 91.64                                           |
| <b>5500</b> | 90.72                                           |
| <b>6000</b> | 90.63                                           |
| <b>6500</b> | 88.48                                           |

*Table 41: Mechanical Efficiency - Part Load*

| <b>RPM</b>  | <b>Load</b> | <b>Mechanical Efficiency-<br/>Part Load (%)</b> |
|-------------|-------------|-------------------------------------------------|
| <b>800</b>  | <b>5</b>    | 50.27                                           |
| <b>1500</b> | <b>10</b>   | 71.13                                           |
| <b>1500</b> | <b>20</b>   | 71.94                                           |
| <b>2000</b> | <b>30</b>   | 78.11                                           |
| <b>2500</b> | <b>20</b>   | 72.89                                           |
| <b>3000</b> | <b>60</b>   | 88.66                                           |
| <b>4000</b> | <b>30</b>   | 57.35                                           |

### 3.6 Specific Fuel Consumption

The specific fuel consumption measures the flow of fuel against the power output of the engine. It can be used to analyse how effectively the engine is converting the fuel into work. It can be obtained using the mass flow rate over power, shown in Equation 35. Alternatively, as engine power can be calculated using Equation 36, the equation for SFC can be re-written as Equation 37. This shows that the SFC is dependent of the engine efficiency and the calorific value of the fuel, and so if either were to be improved, the SFC would also improve.

$$SFC = \frac{\dot{m}_f}{P}$$

Equation 35: SFC from Mass Flow and Power (Heywood, 1988)

$$P = \eta_m \cdot \eta_I \cdot \eta_C \cdot Q \cdot \dot{m}_f$$

Equation 36: Power (Lumley, 1999)

$$SFC = \frac{1}{\eta_m \cdot \eta_I \cdot \eta_C \cdot Q}$$

Equation 37: SFC using Efficiency and Calorific Value (Lumley, 1999)

Table 42: Specific Fuel Consumption (Kg/kWh)

| SFC Kg/kWh | RPM    |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |
|------------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|
|            | 800    | 1000   | 1250   | 1500   | 1750   | 2000   | 2250   | 2500   | 3000   | 3500   | 4000   | 4500   | 5000   | 5500   | 6000   | 6500   |
| FL         |        | 0.2876 | 0.2857 | 0.2863 | 0.2773 | 0.2735 | 0.274  | 0.2729 | 0.2845 | 0.2784 | 0.2732 | 0.2711 | 0.2945 | 0.2955 | 0.3    | 0.2925 |
| 200        |        |        |        |        |        | 0.2737 | 0.2748 | 0.2719 | 0.2825 | 0.2693 |        |        |        |        |        |        |
| 190        |        |        |        |        |        | 0.2705 | 0.2686 | 0.2686 | 0.2839 | 0.2665 |        |        |        |        |        |        |
| 180        |        |        |        |        | 0.2762 | 0.2667 | 0.2652 | 0.2657 | 0.2698 | 0.2701 | 0.2732 |        |        |        |        |        |
| 170        |        |        |        | 0.2855 | 0.2816 | 0.2639 | 0.263  | 0.263  | 0.263  | 0.2737 | 0.2656 | 0.2673 |        |        |        |        |
| 160        |        |        |        | 0.2821 | 0.2756 | 0.2609 | 0.2591 | 0.2598 | 0.2596 | 0.2567 | 0.2607 | 0.2628 | 0.2825 |        |        |        |
| 150        |        |        |        | 0.2775 | 0.2712 | 0.2597 | 0.258  | 0.2596 | 0.2543 | 0.2545 | 0.2567 | 0.2568 | 0.2679 | 0.2832 |        |        |
| 140        |        |        | 0.2846 | 0.2756 | 0.2666 | 0.2588 | 0.2563 | 0.2575 | 0.2505 | 0.2519 | 0.2547 | 0.2522 | 0.2579 | 0.2684 | 0.2908 |        |
| 130        |        |        | 0.2782 | 0.2667 | 0.2584 | 0.2554 | 0.2523 | 0.2512 | 0.246  | 0.2494 | 0.2538 | 0.2512 | 0.2541 | 0.2632 | 0.2804 |        |
| 120        |        |        | 0.2767 | 0.2622 | 0.2617 | 0.2557 | 0.2502 | 0.2478 | 0.2426 | 0.249  | 0.2551 | 0.2517 | 0.2525 | 0.2606 | 0.2712 | 0.2851 |
| 110        |        | 0.2885 | 0.2715 | 0.261  | 0.2602 | 0.251  | 0.2479 | 0.2474 | 0.2435 | 0.2474 | 0.254  | 0.2519 | 0.2529 | 0.2574 | 0.2697 | 0.279  |
| 100        |        | 0.2874 | 0.2618 | 0.263  | 0.2541 | 0.2469 | 0.245  | 0.2473 | 0.2455 | 0.2465 | 0.2501 | 0.2518 | 0.2551 | 0.2603 | 0.2666 | 0.282  |
| 90         |        | 0.2732 | 0.2546 | 0.255  | 0.2491 | 0.2427 | 0.2421 | 0.2451 | 0.2443 | 0.2439 | 0.2493 | 0.2523 | 0.2564 | 0.2622 | 0.2678 | 0.2765 |
| 80         |        | 0.2634 | 0.2538 | 0.2496 | 0.2452 | 0.2411 | 0.2411 | 0.2447 | 0.2432 | 0.2432 | 0.2504 | 0.2537 | 0.2615 | 0.2673 | 0.271  | 0.2799 |
| 70         |        | 0.2592 | 0.253  | 0.2527 | 0.2504 | 0.246  | 0.2464 | 0.2486 | 0.2454 | 0.2463 | 0.2528 | 0.2559 | 0.2651 | 0.2709 | 0.277  | 0.287  |
| 60         |        | 0.2598 | 0.2566 | 0.2556 | 0.2526 | 0.2494 | 0.2506 | 0.2558 | 0.2518 | 0.2518 | 0.2592 | 0.2611 | 0.271  | 0.2779 | 0.2852 | 0.2946 |
| 50         |        | 0.265  | 0.264  | 0.2657 | 0.2602 | 0.2576 | 0.2573 | 0.2604 | 0.26   | 0.262  | 0.2681 | 0.2718 | 0.2792 | 0.2864 | 0.2968 | 0.3066 |
| 40         | 0.3004 | 0.2826 | 0.2783 | 0.278  | 0.2742 | 0.2717 | 0.2732 | 0.2738 | 0.2758 | 0.2798 | 0.2841 | 0.2909 | 0.2991 | 0.3074 | 0.3164 | 0.3283 |
| 30         | 0.3147 | 0.3106 | 0.305  | 0.3053 | 0.303  | 0.3009 | 0.3005 | 0.3005 | 0.3021 | 0.3089 | 0.3138 | 0.3215 | 0.3315 | 0.3427 | 0.3508 | 0.3674 |
| 20         | 0.3624 | 0.37   | 0.356  | 0.3644 | 0.355  | 0.3555 | 0.3508 | 0.3538 | 0.352  | 0.3637 | 0.3737 | 0.3865 | 0.3994 | 0.4136 | 0.4242 | 0.4482 |
| 10         | 0.4897 | 0.5589 | 0.5198 | 0.5154 | 0.5091 | 0.5157 | 0.5098 | 0.5121 | 0.4935 | 0.5258 | 0.5702 | 0.5997 | 0.6132 | 0.6111 | 0.6269 | 0.6576 |
| 5          | 0.7633 | 0.9567 | 0.8581 | 0.8682 | 0.7305 | 0.8264 | 0.8808 | 0.8434 | 0.9638 | 0.8826 | 0.958  | 0.9978 | 1.0695 | 0.9764 | 1.0765 | 1.0882 |
| 2          | 1.8053 | 1.4624 | 3.6526 | 1.7722 | 1.9907 | 1.617  | 1.7946 | 1.1794 | 1.766  | 1.9883 | 2.1759 | 2.1889 |        |        |        |        |

### 3.7 Brake Thermal Efficiency

The brake thermal efficiency is a measure of how efficiently the engine converts the fuel supplied into work (Heywood, 1988). It is more useful than the SFC for the comparison of how effectively the fuel is being used. It is calculated using Equation 38. The brake thermal efficiency of the engine can be seen in Table 43. Figure 14 shows the values of Table 43 in a 3D graph. It shows that the fuel is converted more effectively between 70 and 150 of the load at most RPMs, however 3000RPM to 4500RPM also converts the fuel efficiently at full load. The reason for this pattern will be due to the fuel mapping of the engine and the requirement for fuel to be efficiently converted at the loads and RPMs that will be used the most frequently. Looking at Table 43, only around 30% of the fuel is converted into useful work partially due to inefficiencies in the combustion (Randolph, 2018).

$$\eta_{T,B} = \frac{3.6}{SFC \times Q}$$

Equation 38: Brake Thermal Efficiency (Heywood, 1988)

Table 43: Brake Thermal Efficiency

| Brake Thermal Efficiency (%) | RPM   |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |
|------------------------------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
|                              | 800   | 1000  | 1250  | 1500  | 1750  | 2000  | 2250  | 2500  | 3000  | 3500  | 4000  | 4500  | 5000  | 5500  | 6000  | 6500  |
| FL                           |       | 28.03 | 28.22 | 28.16 | 29.07 | 29.68 | 29.91 | 29.86 | 31.67 | 31.39 | 30.84 | 31.64 | 30.79 | 30.75 | 31.30 | 31.78 |
| 200                          |       |       |       |       |       | 29.66 | 30.00 | 29.94 | 30.71 | 30.26 |       |       |       |       |       |       |
| 190                          |       |       |       |       |       | 30.09 | 30.43 | 30.31 | 31.27 | 32.00 |       |       |       |       |       |       |
| 180                          |       |       |       |       | 29.19 | 30.49 | 30.61 | 30.67 | 31.35 | 32.09 | 30.90 |       |       |       |       |       |
| 170                          |       |       |       | 28.24 | 28.63 | 30.76 | 30.83 | 30.92 | 30.86 | 32.06 | 31.13 | 32.03 |       |       |       |       |
| 160                          |       |       |       | 28.58 | 29.25 | 30.90 | 31.21 | 31.33 | 31.24 | 31.62 | 31.16 | 32.32 | 31.55 |       |       |       |
| 150                          |       |       |       | 29.05 | 29.73 | 31.05 | 31.25 | 31.36 | 31.89 | 31.86 | 31.59 | 32.39 | 31.83 | 31.15 |       |       |
| 140                          |       |       | 28.33 | 29.25 | 30.24 | 31.15 | 31.46 | 31.40 | 32.28 | 32.22 | 31.84 | 32.12 | 31.75 | 31.87 | 31.48 |       |
| 130                          |       |       | 28.98 | 30.23 | 31.20 | 31.57 | 31.96 | 32.10 | 32.77 | 32.61 | 31.98 | 32.25 | 31.76 | 32.14 | 31.62 |       |
| 120                          |       |       | 29.14 | 30.75 | 30.81 | 31.53 | 32.22 | 32.54 | 33.23 | 32.66 | 31.79 | 32.03 | 31.93 | 31.69 | 32.02 | 31.33 |
| 110                          |       | 27.95 | 29.70 | 30.89 | 30.99 | 32.12 | 32.52 | 32.59 | 33.11 | 32.75 | 31.80 | 32.01 | 31.88 | 31.32 | 31.65 | 31.03 |
| 100                          |       | 28.05 | 30.80 | 30.66 | 31.73 | 32.65 | 32.91 | 32.60 | 32.84 | 32.71 | 32.24 | 32.02 | 31.61 | 30.97 | 30.62 | 30.67 |
| 90                           |       | 29.51 | 31.67 | 31.62 | 32.37 | 33.22 | 33.30 | 32.89 | 33.00 | 33.06 | 32.34 | 31.96 | 31.44 | 30.75 | 30.11 | 29.16 |
| 80                           |       | 30.61 | 31.77 | 32.30 | 32.88 | 33.44 | 33.44 | 32.95 | 33.15 | 33.15 | 32.20 | 31.78 | 30.83 | 30.16 | 29.75 | 28.80 |
| 70                           |       | 31.11 | 31.87 | 31.91 | 32.20 | 32.77 | 32.72 | 32.43 | 32.85 | 32.73 | 31.89 | 31.51 | 30.41 | 29.76 | 29.11 | 28.09 |
| 60                           |       | 31.03 | 31.42 | 31.54 | 31.92 | 32.33 | 32.17 | 31.52 | 32.02 | 32.02 | 31.11 | 30.88 | 29.75 | 29.01 | 28.27 | 27.37 |
| 50                           |       | 30.42 | 30.54 | 30.34 | 30.99 | 31.30 | 31.33 | 30.96 | 31.01 | 30.77 | 30.07 | 29.66 | 28.88 | 28.15 | 27.16 | 26.30 |
| 40                           | 26.84 | 28.53 | 28.97 | 29.00 | 29.40 | 29.67 | 29.51 | 29.45 | 29.23 | 28.82 | 28.38 | 27.72 | 26.96 | 26.23 | 25.48 | 24.56 |
| 30                           | 25.62 | 25.96 | 26.43 | 26.41 | 26.61 | 26.79 | 26.83 | 26.83 | 26.69 | 26.10 | 25.69 | 25.08 | 24.32 | 23.53 | 22.98 | 21.94 |
| 20                           | 22.25 | 21.79 | 22.65 | 22.13 | 22.71 | 22.68 | 22.98 | 22.79 | 22.90 | 22.17 | 21.57 | 20.86 | 20.19 | 19.49 | 19.01 | 17.99 |
| 10                           | 16.46 | 14.43 | 15.51 | 15.64 | 15.84 | 15.63 | 15.81 | 15.74 | 16.34 | 15.33 | 14.14 | 13.44 | 13.15 | 13.19 | 12.86 | 12.26 |
| 5                            | 10.56 | 8.43  | 9.40  | 9.29  | 11.04 | 9.76  | 9.15  | 9.56  | 8.37  | 9.13  | 8.42  | 8.08  | 7.54  | 8.26  | 7.49  | 7.41  |
| 2                            | 4.47  | 5.51  | 2.21  | 4.55  | 4.05  | 4.99  | 4.49  | 6.84  | 4.57  | 4.05  | 3.71  | 3.68  |       |       |       |       |

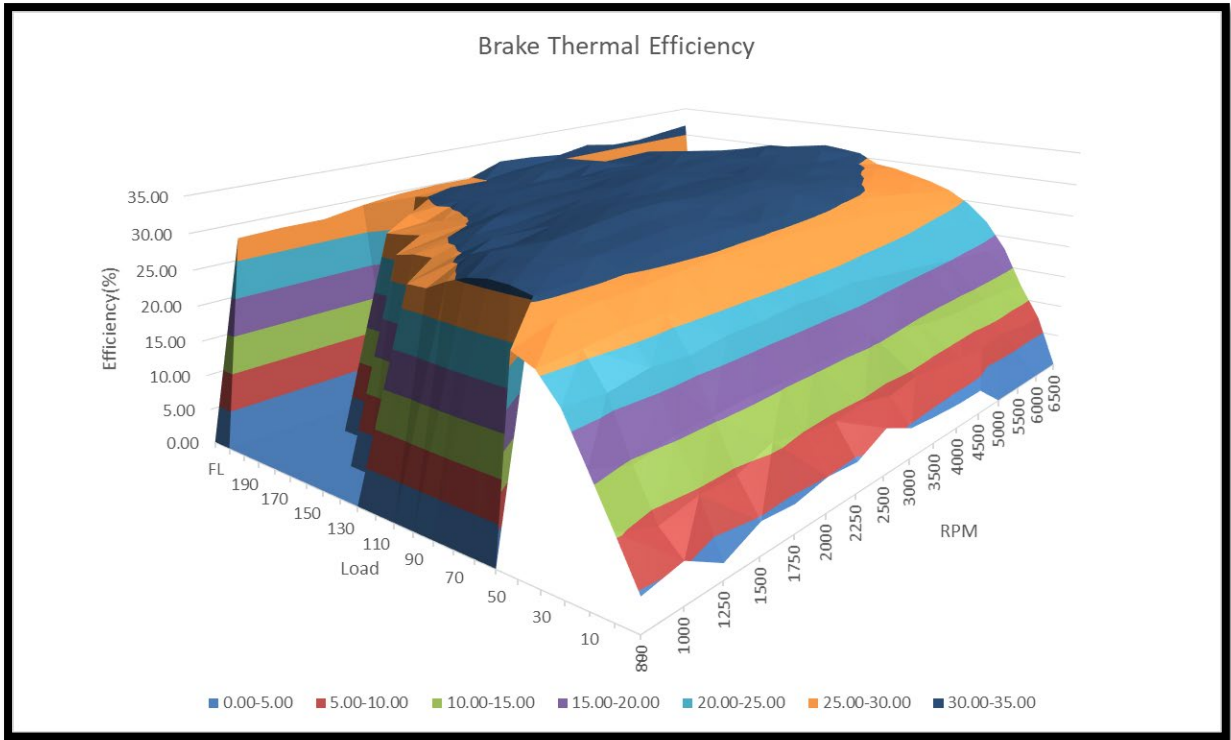


Figure 14: Brake Thermal Efficiency

### 3.8 Indicated Thermal Efficiency

The indicated thermal efficiency is the thermal efficiency calculated before any losses such as friction have been considered. It can be calculated using the fuel conversion efficiency and the relationship between the FMEP and BMEP shown in Equation 39.

$$\eta_{T,I} = \eta_{T,B} \times \left(1 + \frac{FMEP}{BMEP}\right)$$

Equation 39: Indicated Thermal Efficiency (Heywood, 1988)

Table 44 and Table 45 show a comparison between the brake and indicated thermal efficiency values. The differences can be seen graphically represented in Figure 15.

Table 44: Indicated Thermal Efficiency - Full Load

| RPM  | FMEP/BMEP | Brake Thermal Efficiency | Indicated Thermal Efficiency |
|------|-----------|--------------------------|------------------------------|
|      |           | %                        | %                            |
| 1000 | 0.0836    | 28.03                    | 30.38                        |
| 1250 | 0.0681    | 28.22                    | 30.14                        |
| 1500 | 0.0602    | 28.16                    | 29.86                        |
| 1750 | 0.0606    | 29.07                    | 30.84                        |
| 2000 | 0.0630    | 29.68                    | 31.55                        |
| 2250 | 0.0684    | 29.91                    | 31.96                        |
| 2500 | 0.0729    | 29.86                    | 32.03                        |
| 3000 | 0.0586    | 31.67                    | 33.52                        |
| 3500 | 0.0807    | 31.39                    | 33.92                        |
| 4000 | 0.0784    | 30.84                    | 33.26                        |
| 4500 | 0.0836    | 31.64                    | 34.29                        |
| 5000 | 0.0912    | 30.79                    | 33.60                        |
| 5500 | 0.1023    | 30.75                    | 33.90                        |
| 6000 | 0.1034    | 31.30                    | 34.54                        |
| 6500 | 0.1302    | 31.78                    | 35.92                        |

Table 45: Indicated Thermal Efficiency - Part Load

| RPM  | Load | FMEP/BMEP | Brake Thermal Efficiency | Indicated Thermal Efficiency |
|------|------|-----------|--------------------------|------------------------------|
|      |      |           | %                        | %                            |
| 800  | 5    | 0.9892    | 10.56                    | 21.01                        |
| 1500 | 10   | 0.4059    | 15.64                    | 21.99                        |
| 1500 | 20   | 0.3900    | 22.13                    | 30.75                        |
| 2000 | 30   | 0.2803    | 26.79                    | 34.30                        |
| 2500 | 20   | 0.3720    | 22.79                    | 31.27                        |
| 3000 | 60   | 0.1279    | 31.01                    | 34.97                        |
| 4000 | 30   | 0.7438    | 26.10                    | 45.51                        |

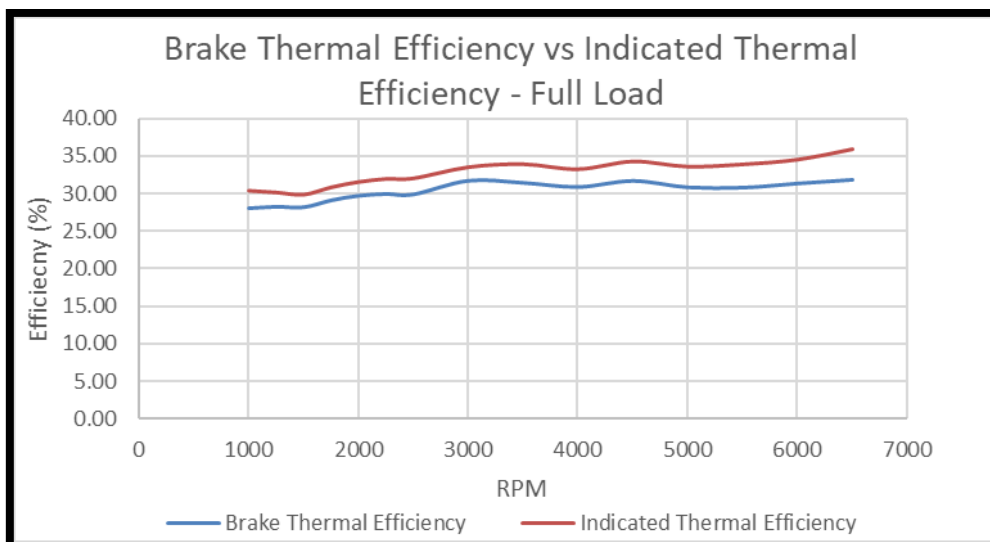


Figure 15: Brake Thermal Efficiency vs Indicated Thermal Efficiency - Full Load

### 3.9 Exhaust Energy

From the fuel energy put into the engine shown in Table 46, only around 30% becomes useful work output to the flywheel as can be seen in Table 43. The remaining 70% is lost through heat transfer into the oil and water systems and down the exhaust. It is possible to use the method below to define the percentage of fuel energy lost down the exhaust.

Table 46: Fuel Energy (KJ/S)

| Fuel Energy/Second<br>(KJ/S) | RPM  |      |      |      |       |       |       |       |       |       |       |       |       |       |       |       |
|------------------------------|------|------|------|------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
|                              | 800  | 1000 | 1250 | 1500 | 1750  | 2000  | 2250  | 2500  | 3000  | 3500  | 4000  | 4500  | 5000  | 5500  | 6000  | 6500  |
| FL                           |      | 40.2 | 64.7 | 93.3 | 116.5 | 139.8 | 157.6 | 176.0 | 200.7 | 216.5 | 255.7 | 280.4 | 281.8 | 292.8 | 294.1 | 270.1 |
| 200                          |      |      |      |      |       | 139.7 | 157.2 | 175.1 | 204.9 | 239.0 |       |       |       |       |       |       |
| 190                          |      |      |      |      |       | 132.3 | 147.2 | 164.5 | 190.5 | 216.5 |       |       |       |       |       |       |
| 180                          |      |      |      |      | 113.0 | 123.6 | 138.7 | 153.7 | 180.2 | 204.9 | 244.2 |       |       |       |       |       |
| 170                          |      |      |      | 93.1 | 108.8 | 115.6 | 129.7 | 144.1 | 173.2 | 195.3 | 228.7 | 250.1 |       |       |       |       |
| 160                          |      |      |      | 88.1 | 100.2 | 108.4 | 120.8 | 133.7 | 160.9 | 185.5 | 214.9 | 233.1 | 265.7 |       |       |       |
| 150                          |      |      |      | 80.9 | 92.5  | 101.3 | 113.1 | 125.2 | 147.7 | 172.6 | 199.5 | 218.2 | 246.2 | 277.4 |       |       |
| 140                          |      |      | 64.4 | 74.9 | 84.8  | 94.6  | 104.8 | 116.8 | 136.2 | 159.3 | 183.4 | 205.5 | 231.1 | 252.9 | 279.4 |       |
| 130                          |      |      | 58.7 | 67.7 | 76.4  | 86.3  | 95.9  | 106.0 | 124.7 | 146.2 | 170.5 | 190.1 | 214.4 | 233.0 | 258.6 |       |
| 120                          |      |      | 54.0 | 61.1 | 71.3  | 79.3  | 87.7  | 96.6  | 113.5 | 134.6 | 158.6 | 176.6 | 197.0 | 217.9 | 235.5 | 260.8 |
| 110                          |      | 39.9 | 48.5 | 56.1 | 65.0  | 71.7  | 79.8  | 88.4  | 104.4 | 123.1 | 144.2 | 162.0 | 180.8 | 202.3 | 218.6 | 241.4 |
| 100                          |      | 36.8 | 42.5 | 51.2 | 57.8  | 64.5  | 71.7  | 80.4  | 95.6  | 112.0 | 130.6 | 147.3 | 166.0 | 186.0 | 205.5 | 222.1 |
| 90                           |      | 31.8 | 37.2 | 44.7 | 51.0  | 56.4  | 63.6  | 71.6  | 85.6  | 99.8  | 116.1 | 132.7 | 150.2 | 168.6 | 187.9 | 210.2 |
| 80                           |      | 27.3 | 33.0 | 39.1 | 44.5  | 50.2  | 56.4  | 63.6  | 75.8  | 88.4  | 104.1 | 118.6 | 135.8 | 152.8 | 169.2 | 189.1 |
| 70                           |      | 23.4 | 28.9 | 34.4 | 39.8  | 44.7  | 50.5  | 56.6  | 67.0  | 78.4  | 92.4  | 104.7 | 120.4 | 135.4 | 151.1 | 169.8 |
| 60                           |      | 20.2 | 25.1 | 30.0 | 34.5  | 38.7  | 43.9  | 49.9  | 58.9  | 68.7  | 80.6  | 91.7  | 105.6 | 119.1 | 133.5 | 149.3 |
| 50                           |      | 17.1 | 21.5 | 25.8 | 29.5  | 33.5  | 37.6  | 42.3  | 50.7  | 59.5  | 69.5  | 79.5  | 90.7  | 102.3 | 115.7 | 129.2 |
| 40                           | 12.9 | 14.4 | 18.1 | 21.8 | 24.9  | 28.3  | 31.9  | 35.6  | 42.9  | 50.9  | 59.2  | 68.0  | 77.8  | 88.1  | 98.5  | 110.6 |
| 30                           | 11.0 | 11.8 | 14.8 | 17.6 | 20.7  | 23.3  | 26.4  | 29.3  | 35.3  | 42.3  | 48.9  | 56.4  | 64.6  | 73.7  | 82.1  | 93.1  |
| 20                           | 7.6  | 9.1  | 11.5 | 13.6 | 16.1  | 18.4  | 20.5  | 22.8  | 27.4  | 33.1  | 38.8  | 45.1  | 51.8  | 59.0  | 66.6  | 75.4  |
| 10                           | 5.5  | 6.3  | 8.1  | 9.7  | 11.5  | 13.0  | 14.4  | 16.0  | 20.2  | 23.8  | 29.5  | 33.7  | 39.4  | 45.1  | 51.8  | 59.4  |
| 5                            | 4.5  | 5.2  | 6.6  | 7.8  | 9.8   | 10.9  | 12.2  | 13.5  | 16.4  | 19.8  | 24.7  | 28.9  | 33.9  | 38.9  | 44.2  | 50.6  |
| 2                            | 4.0  | 4.8  | 5.7  | 6.9  | 8.2   | 9.7   | 10.7  | 12.2  | 15.1  | 17.9  | 22.7  | 25.9  |       |       |       |       |

Table 47: Energy Lost (KJ/s)

| Energy<br>Lost/Second<br>(KJ/s) | RPM   |       |        |        |        |        |        |        |        |        |         |         |         |         |         |         |
|---------------------------------|-------|-------|--------|--------|--------|--------|--------|--------|--------|--------|---------|---------|---------|---------|---------|---------|
|                                 | 800   | 1000  | 1250   | 1500   | 1750   | 2000   | 2250   | 2500   | 3000   | 3500   | 4000    | 4500    | 5000    | 5500    | 6000    | 6500    |
| FL                              |       | 9.689 | 17.779 | 27.985 | 37.028 | 48.216 | 56.415 | 65.928 | 79.287 | 86.660 | 103.987 | 105.719 | 120.695 | 125.598 | 125.713 | 110.361 |
| 200                             |       |       |        |        |        | 48.193 | 56.473 | 65.441 | 79.304 | 95.817 |         |         |         |         |         |         |
| 190                             |       |       |        |        |        | 44.802 | 51.540 | 60.201 | 73.044 | 86.183 |         |         |         |         |         |         |
| 180                             |       |       |        |        | 35.442 | 40.928 | 47.637 | 55.148 | 67.775 | 79.033 | 97.967  |         |         |         |         |         |
| 170                             |       |       |        | 27.917 | 33.104 | 37.464 | 43.718 | 50.529 | 63.525 | 71.812 | 89.070  | 99.768  |         |         |         |         |
| 160                             |       |       |        | 26.097 | 30.184 | 34.312 | 39.626 | 45.567 | 57.552 | 68.180 | 81.504  | 90.447  | 110.302 |         |         |         |
| 150                             |       |       |        | 23.591 | 27.695 | 31.191 | 35.911 | 41.276 | 51.072 | 61.820 | 73.696  | 82.264  | 97.410  | 115.797 |         |         |
| 140                             |       |       | 17.694 | 21.513 | 25.010 | 28.160 | 32.213 | 37.052 | 45.550 | 55.513 | 65.838  | 75.355  | 87.702  | 99.486  | 116.583 |         |
| 130                             |       |       | 15.726 | 18.982 | 21.911 | 24.690 | 28.179 | 32.178 | 40.110 | 49.404 | 59.678  | 67.721  | 78.493  | 88.304  | 104.107 |         |
| 120                             |       |       | 14.352 | 16.484 | 18.833 | 22.155 | 25.060 | 28.217 | 35.183 | 44.393 | 54.460  | 61.530  | 69.400  | 80.140  | 89.672  | 104.602 |
| 110                             |       | 9.503 | 12.623 | 14.881 | 16.765 | 19.440 | 22.331 | 25.254 | 31.739 | 39.458 | 48.233  | 55.306  | 62.010  | 71.594  | 81.259  | 93.155  |
| 100                             |       | 7.835 | 10.685 | 12.524 | 14.727 | 17.159 | 19.680 | 22.584 | 28.431 | 35.182 | 42.300  | 49.300  | 56.281  | 65.077  | 74.230  | 84.059  |
| 90                              |       | 6.624 | 8.940  | 10.681 | 12.758 | 14.784 | 17.212 | 19.840 | 25.097 | 30.669 | 36.964  | 43.774  | 50.147  | 57.809  | 66.520  | 77.433  |
| 80                              |       | 5.417 | 7.349  | 9.138  | 10.935 | 12.719 | 14.936 | 17.388 | 22.001 | 26.706 | 32.884  | 38.523  | 44.907  | 52.187  | 58.835  | 68.054  |
| 70                              |       | 4.466 | 6.200  | 7.858  | 9.542  | 11.011 | 13.055 | 15.106 | 18.842 | 23.123 | 28.634  | 33.390  | 39.418  | 45.313  | 51.914  | 60.113  |
| 60                              |       | 3.669 | 5.104  | 6.528  | 7.829  | 9.158  | 10.905 | 12.981 | 16.266 | 19.811 | 24.488  | 28.644  | 34.030  | 39.317  | 45.275  | 51.958  |
| 50                              |       | 2.975 | 4.143  | 5.356  | 6.386  | 7.537  | 8.858  | 10.461 | 13.543 | 16.772 | 20.614  | 24.358  | 28.742  | 33.051  | 38.639  | 44.230  |
| 40                              | 1.934 | 2.399 | 3.326  | 4.283  | 5.081  | 5.989  | 7.207  | 8.421  | 11.118 | 13.991 | 17.067  | 20.391  | 24.310  | 28.236  | 32.540  | 37.473  |
| 30                              | 1.567 | 1.831 | 2.561  | 3.297  | 4.069  | 4.744  | 5.767  | 6.708  | 8.811  | 11.271 | 13.718  | 16.591  | 19.845  | 23.449  | 26.745  | 31.156  |
| 20                              | 0.914 | 1.266 | 1.837  | 2.450  | 3.083  | 3.703  | 4.334  | 5.082  | 6.610  | 8.574  | 10.660  | 13.145  | 15.701  | 18.365  | 21.005  | 24.535  |
| 10                              | 0.621 | 0.831 | 1.292  | 1.649  | 2.114  | 2.473  | 2.863  | 3.303  | 4.682  | 5.951  | 7.992   | 9.582   | 11.639  | 13.501  | 15.735  | 18.628  |
| 5                               | 0.389 | 0.585 | 0.986  | 1.310  | 1.830  | 2.267  | 2.596  | 2.953  | 3.961  | 5.036  | 6.651   | 8.042   | 9.778   | 11.295  | 12.833  | 15.412  |
| 2                               | 0.328 | 0.526 | 0.823  | 1.028  | 1.398  | 1.985  | 2.167  | 2.649  | 3.803  | 4.732  | 6.116   | 7.175   |         |         |         |         |

Table 48: Percentage Fuel Energy Lost down Exhaust

| % Fuel Energy<br>Lost Down Exhaust | RPM   |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |
|------------------------------------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
|                                    | 800   | 1000  | 1250  | 1500  | 1750  | 2000  | 2250  | 2500  | 3000  | 3500  | 4000  | 4500  | 5000  | 5500  | 6000  | 6500  |
| FL                                 |       | 24.11 | 27.46 | 30.00 | 31.79 | 34.48 | 35.79 | 37.46 | 39.51 | 40.03 | 40.67 | 40.60 | 42.83 | 42.89 | 42.74 | 40.86 |
| 200                                |       |       |       |       |       | 34.49 | 35.92 | 37.38 | 38.70 | 40.10 |       |       |       |       |       |       |
| 190                                |       |       |       |       |       | 33.86 | 35.01 | 36.60 | 38.34 | 39.81 |       |       |       |       |       |       |
| 180                                |       |       |       |       | 31.37 | 33.12 | 34.34 | 35.89 | 37.62 | 38.57 | 40.13 |       |       |       |       |       |
| 170                                |       |       |       | 29.97 | 30.43 | 32.42 | 33.70 | 35.06 | 36.67 | 36.76 | 38.94 | 39.89 |       |       |       |       |
| 160                                |       |       |       | 29.63 | 30.12 | 31.65 | 32.79 | 34.09 | 35.76 | 36.75 | 37.93 | 38.79 | 41.52 |       |       |       |
| 150                                |       |       |       | 29.17 | 29.93 | 30.78 | 31.75 | 32.97 | 34.57 | 35.81 | 36.93 | 37.69 | 39.57 | 41.74 |       |       |
| 140                                |       |       | 27.49 | 28.72 | 29.48 | 29.76 | 30.74 | 31.74 | 33.45 | 34.85 | 35.90 | 36.66 | 37.95 | 39.34 | 41.73 |       |
| 130                                |       |       | 26.81 | 28.03 | 28.68 | 28.60 | 29.39 | 30.34 | 32.18 | 33.79 | 35.00 | 35.62 | 36.62 | 37.90 | 40.26 |       |
| 120                                |       |       | 26.60 | 26.96 | 26.41 | 27.95 | 28.58 | 29.20 | 31.00 | 32.97 | 34.34 | 34.84 | 35.24 | 36.77 | 38.08 | 40.10 |
| 110                                |       | 23.79 | 26.03 | 26.54 | 25.80 | 27.12 | 28.00 | 28.56 | 30.39 | 32.06 | 33.44 | 34.14 | 34.29 | 35.39 | 37.17 | 38.59 |
| 100                                |       | 21.27 | 25.12 | 24.45 | 25.48 | 26.61 | 27.45 | 28.10 | 29.73 | 31.41 | 32.39 | 33.46 | 33.91 | 34.98 | 36.11 | 37.85 |
| 90                                 |       | 20.86 | 24.03 | 23.92 | 25.03 | 26.20 | 27.05 | 27.72 | 29.33 | 30.72 | 31.84 | 32.98 | 33.39 | 34.30 | 35.40 | 36.83 |
| 80                                 |       | 19.85 | 22.27 | 23.39 | 24.56 | 25.32 | 26.47 | 27.33 | 29.03 | 30.20 | 31.60 | 32.49 | 33.07 | 34.15 | 34.78 | 35.98 |
| 70                                 |       | 19.05 | 21.45 | 22.87 | 23.97 | 24.66 | 25.86 | 26.71 | 28.13 | 29.50 | 30.99 | 31.90 | 32.73 | 33.46 | 34.36 | 35.40 |
| 60                                 |       | 18.15 | 20.37 | 21.75 | 22.71 | 23.67 | 24.84 | 26.03 | 27.61 | 28.83 | 30.37 | 31.25 | 32.24 | 33.02 | 33.92 | 34.79 |
| 50                                 |       | 17.38 | 19.31 | 20.76 | 21.63 | 22.51 | 23.57 | 24.73 | 26.70 | 28.17 | 29.68 | 30.64 | 31.70 | 32.30 | 33.39 | 34.22 |
| 40                                 | 14.99 | 16.67 | 18.37 | 19.62 | 20.38 | 21.18 | 22.61 | 23.66 | 25.91 | 27.51 | 28.85 | 30.00 | 31.26 | 32.06 | 33.04 | 33.87 |
| 30                                 | 14.19 | 15.54 | 17.35 | 18.72 | 19.65 | 20.35 | 21.83 | 22.92 | 24.93 | 26.65 | 28.07 | 29.40 | 30.71 | 31.83 | 32.57 | 33.45 |
| 20                                 | 12.08 | 13.98 | 15.92 | 17.96 | 19.12 | 20.17 | 21.18 | 22.27 | 24.11 | 25.89 | 27.46 | 29.12 | 30.28 | 31.11 | 31.54 | 32.53 |
| 10                                 | 11.39 | 13.14 | 16.03 | 17.05 | 18.32 | 18.99 | 19.90 | 20.64 | 23.16 | 24.99 | 27.07 | 28.40 | 29.51 | 29.91 | 30.35 | 31.35 |
| 5                                  | 8.70  | 11.24 | 14.99 | 16.76 | 18.68 | 20.77 | 21.36 | 21.84 | 24.19 | 25.37 | 26.95 | 27.83 | 28.88 | 29.00 | 29.06 | 30.46 |
| 2                                  | 8.26  | 10.88 | 14.43 | 14.80 | 17.07 | 20.52 | 20.32 | 21.80 | 25.13 | 26.49 | 26.94 | 27.68 |       |       |       |       |

## 4 Otto Cycle Efficiency

This chapter considers the Otto cycle. The pressure-volume data and the values of the temperature obtained in the Pressure Volume Data chapter are used to calculate the thermal efficiency of the Otto cycle. An ideal Otto cycle of the engine and its efficiency are then calculated and discussed. A definition of the Otto cycle can be seen in the appendix.

### 4.1 Specific Heats

There are two types of specific heat used in this study. The specific heat at constant pressure ( $\widetilde{C}_p$ ) and the specific heat at constant volume ( $\widetilde{C}_v$ ). The  $\widetilde{C}_p$  shows the relationship between the enthalpy of the molecule and temperature at a constant pressure and can be shown as the slope of the enthalpy-temperature curve when plotted. The  $\widetilde{C}_v$  shows the relationship between the internal energy of the molecule and temperature at a constant volume, this is shown to be the slope of an internal energy vs temperature curve. It is possible to see from that the specific heat values of an ideal are dependent on temperature. This results from the diatomic structure of the molecule and the 3 components of its internal energy; translation, rotation, and vibration (Figure 16), (Turns, 2006). Equation 40 and Equation 41 show how the values are obtained and further reinforces the dependence of the specific heats on temperatures. The ratio of the specific heats ( $\gamma$ ) is a frequently used value and is defined in Equation 42.

$$\widetilde{C}_v = \left(\frac{\partial u}{\partial T}\right)_v = \frac{\partial u}{\partial T}$$

*Equation 40: Specific Heat at constant volume (Heywood, 1988)*

$$\widetilde{C}_p = \left(\frac{\partial h}{\partial T}\right)_p = \frac{\partial h}{\partial T}$$

*Equation 41: Specific Heat at constant pressure (Heywood, 1988)*

$$\gamma = \frac{\widetilde{C}_p}{\widetilde{C}_v}$$

*Equation 42: Ratio of Specific Heats (Heywood, 1988)*

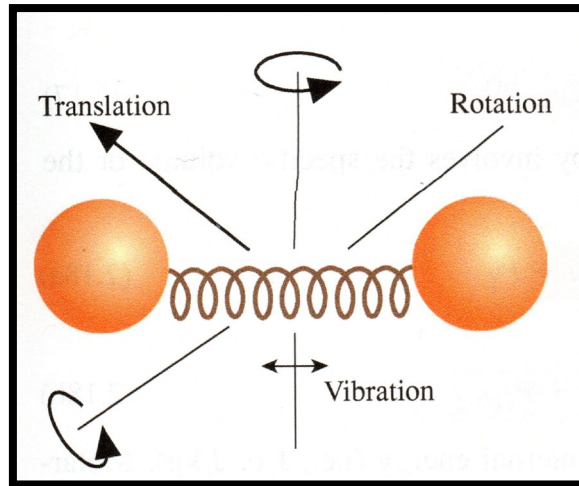


Figure 16: Diatomic Molecule Internal Energies (Turns, 2006)

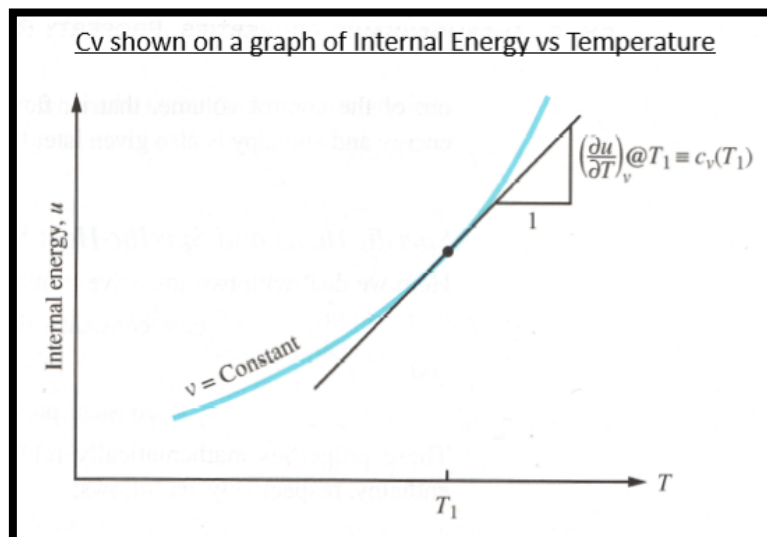


Figure 17: Cv shown on a graph of Internal Energy vs Temperature (Turns, 2006)

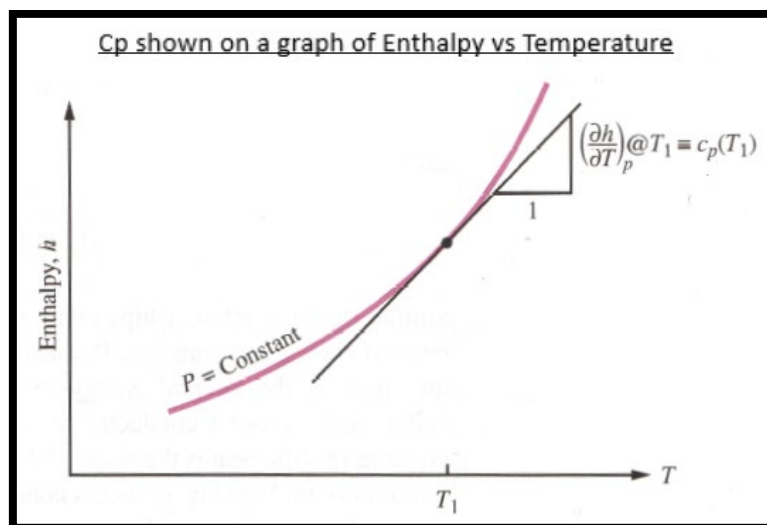


Figure 18: Cp shown on a graph of Enthalpy vs Temperature (Turns, 2006)

The specific heats at constant pressure and constant volume form an important component of this study. They are frequently used in the various efficiency calculations. The  $\widetilde{C}_p$  of each component of the air:fuel mixture needed to first be obtained to be able to obtain the  $\widetilde{C}_p$  of the mixture overall and from that the overall  $\widetilde{C}_v$  value. It was discovered that there are 2 methods of calculating the  $\widetilde{C}_p$  values which are described below:

- The first method used to calculate the  $\widetilde{C}_p$  was by using polynomials. To do this  $\widetilde{C}_p$  and temperature data from tables of the thermodynamic properties of the ideal gases (shown in Appendix: Thermodynamic Property Tables (Turns, 2006)) was plotted onto a graph. The polynomial equation of the curve was then generated and used in the calculation of the  $\widetilde{C}_p$  values from the engine data. An example of the graph and polynomial can be seen in Figure 19. To calculate the  $\widetilde{C}_p$  (shown as y in polynomial), the temperature at each degree was inputted in place of the x values in the polynomial. This method was only applicable to the calculation of Oxygen and Nitrogen  $\widetilde{C}_p$  values.

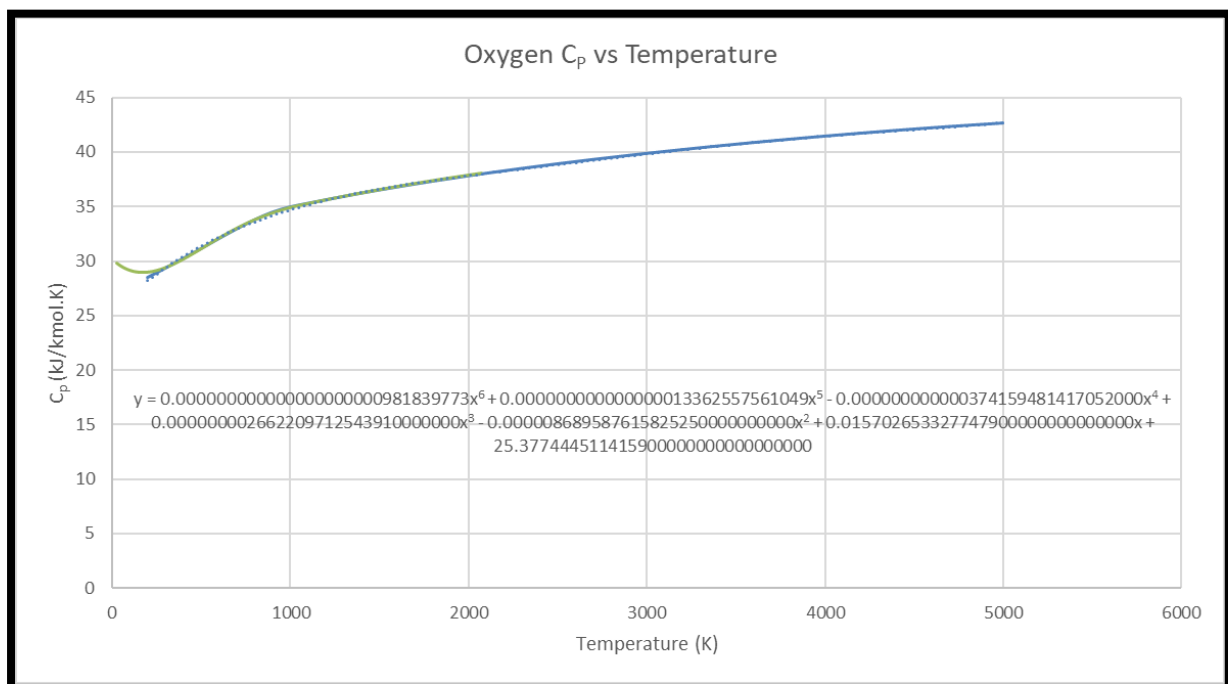


Figure 19: Graph and Polynomial to calculate  $C_p$  of Oxygen

- The second method of generating the  $\widetilde{C}_p$  values is using curve fit coefficients described in Heywood and Turns. This method uses a series of equations and values. Equation 43 shows the method used to calculate the  $\widetilde{C}_p$  of Isooctane. Equation 44 shows the method used to calculate the  $\widetilde{C}_p$  values of Nitrogen and Oxygen. The calculations for Nitrogen and Oxygen require different figures to be inputted into the equation at different temperature ranges. The values to be inputted in place of "a" can be seen in Appendix: Molecular Thermodynamic Properties (Heywood, 1988) (Turns, 2006).

$$\widetilde{C}_p \text{ Isooctane } (kJ/kmol.k) = 4.184(a_1 + a_2 \frac{T}{1000} + a_3 \frac{T^2}{1000} + a_4 \frac{T^3}{1000} + a_5 \frac{T^{-2}}{1000})$$

Equation 43:  $C_p$  Isooctane (Turns, 2006)

$$\widetilde{C}_p (kJ/kmol.k) = \widetilde{R}(a_1 + a_2 T + a_3 T^2 + a_4 T^3 + a_5 T^4)$$

Once the  $C_p$  values have been calculated for each molecule it is possible to work out the overall  $C_p$  value of the mixture. This is achieved in Equation 45.

$$\widetilde{C_pMixture}(kJ/kmol.K) = \frac{(FER \times \widetilde{C_pIsooctane}) + 12.5(\widetilde{C_pOxygen} + (3.76 \times \widetilde{C_pNitrogen}))}{FER + 12.5(1 + 3.76)}$$

After the  $\widetilde{C_p}$  of the mixture has been obtained, the overall  $\widetilde{C_v}$  values can be calculated using Equation 46 .

$$\widetilde{C_vMixture}(kJ/kmol.K) = \widetilde{C_pMixture} - \widetilde{R}$$

Table 49 and Table 50 show an extract of the specific heat values calculated from the Ford data using both the polynomial method and the curve coefficient method. The values of Isooctane remain the same as only one method of calculation was available. However, the different methods give slightly different results for the  $\widetilde{C_p}$  value of oxygen and nitrogen, resulting in differences in the  $\widetilde{C_v}$  and  $\gamma$  values although minor. This is further reinforced by Figure 20 which shows a graph of  $\widetilde{C_p}$  vs Temperature for the 2 methods and the values from the thermodynamic property table. The curve plotted from the thermodynamic property data table is assumed to be the datum and so the calculation accuracy will be determined from how closely they match its data. From examining Figure 20, the curves all follow the same trend. However, it appears the curve from the curve fit coefficient data is following the trend set by the thermodynamic property table more closely than the polynomial equation. It is reasonable to assume that if the polynomial was calculated to more decimal places then it would match the thermodynamic more accurately. The differences between the calculated values are so minute there is no obvious method that provides more accurate results. Therefore, both methods of calculating the specific heats will be used and compared throughout the study. Figure 20 shows that at lower temperatures there are anomalies in the curves. This can be attributed to errors in the temperature calculation caused by the inlet valve opening. As a result, any values below 300 Kelvin are irrelevant. When looking at Figure 20 it is possible to see that as the temperature rises, the  $\widetilde{C_p}$  also rises. Figure 21 shows the ratio of specific heats plotted against temperature. It shows that as the temperature increases, the value of the ratio of specific heat decreases.

Table 49: Extract of Specific Heat Data at 6500 RPM Full Load using Polynomials

| Crank Angle | Volume         | 6500RPM - Polynomial      |                     |                        |                     |                       |                    |                    | $\gamma$ |
|-------------|----------------|---------------------------|---------------------|------------------------|---------------------|-----------------------|--------------------|--------------------|----------|
|             |                | Average Cylinder Pressure | Average Temperature | Cp Average - Isooctane | Cp Average - Oxygen | Cp Average - Nitrogen | Cp Average Overall | Cv Average Overall |          |
| Degrees     | m <sup>3</sup> | Pascals                   | Kelvin              | KJ/Kmol.K              | KJ/Kmol.K           | KJ/Kmol.K             | KJ/Kmol.K          | KJ/Kmol.K          |          |
| -10         | 4.03E-05       | 3458300                   | 774.848             | 380.343                | 33.435              | 31.288                | 38.100             | 29.785             | 1.279    |
| -9          | 3.97E-05       | 3538466.667               | 780.625             | 381.954                | 33.472              | 31.321                | 38.162             | 29.848             | 1.279    |
| -8          | 3.92E-05       | 3615266.667               | 786.323             | 383.530                | 33.508              | 31.354                | 38.224             | 29.909             | 1.278    |
| -7          | 3.87E-05       | 3669800                   | 788.197             | 384.045                | 33.519              | 31.364                | 38.244             | 29.930             | 1.278    |
| -6          | 3.82E-05       | 3720666.667               | 790.236             | 384.604                | 33.532              | 31.376                | 38.266             | 29.951             | 1.278    |
| -5          | 3.79E-05       | 3793433.333               | 798.106             | 386.746                | 33.581              | 31.421                | 38.350             | 30.036             | 1.277    |
| -4          | 3.76E-05       | 3865100                   | 806.744             | 389.066                | 33.634              | 31.470                | 38.442             | 30.127             | 1.276    |
| -3          | 3.74E-05       | 3944466.667               | 818.271             | 392.116                | 33.704              | 31.536                | 38.563             | 30.248             | 1.275    |
| -2          | 3.72E-05       | 3996900                   | 825.596             | 394.027                | 33.748              | 31.578                | 38.639             | 30.325             | 1.274    |
| -1          | 3.71E-05       | 4082500                   | 841.010             | 397.977                | 33.840              | 31.666                | 38.798             | 30.484             | 1.273    |
| 0           | 3.71E-05       | 4194766.667               | 863.205             | 403.504                | 33.969              | 31.792                | 39.024             | 30.709             | 1.271    |
| 1           | 3.71E-05       | 4319666.667               | 889.867             | 409.897                | 34.119              | 31.943                | 39.289             | 30.974             | 1.268    |
| 2           | 3.72E-05       | 4453833.333               | 919.980             | 416.808                | 34.283              | 32.113                | 39.580             | 31.266             | 1.266    |
| 3           | 3.74E-05       | 4605033.333               | 955.304             | 424.513                | 34.469              | 32.310                | 39.911             | 31.597             | 1.263    |
| 4           | 3.76E-05       | 4802266.667               | 1002.354            | 434.141                | 34.704              | 32.567                | 40.336             | 32.021             | 1.260    |
| 5           | 3.79E-05       | 5030433.333               | 1058.360            | 444.723                | 34.969              | 32.867                | 40.815             | 32.501             | 1.256    |
| 6           | 3.82E-05       | 5265966.667               | 1118.444            | 455.113                | 35.235              | 33.177                | 41.301             | 32.986             | 1.252    |
| 7           | 3.87E-05       | 5530533.333               | 1187.536            | 465.970                | 35.519              | 33.519                | 41.822             | 33.508             | 1.248    |
| 8           | 3.92E-05       | 5817433.333               | 1264.973            | 476.952                | 35.814              | 33.880                | 42.364             | 34.049             | 1.244    |
| 9           | 3.97E-05       | 6129933.333               | 1351.991            | 488.083                | 36.119              | 34.256                | 42.921             | 34.607             | 1.240    |
| 10          | 4.03E-05       | 6437633.333               | 1442.024            | 498.600                | 36.409              | 34.612                | 43.449             | 35.134             | 1.237    |

Table 50: Extract of Specific Heat Data at 6500 RPM Full Load using Curve Coefficient

| Crank Angle | Volume         | 6500RPM - Curve Coefficient |                     |                        |                     |                       |                    |                    | $\gamma$ |
|-------------|----------------|-----------------------------|---------------------|------------------------|---------------------|-----------------------|--------------------|--------------------|----------|
|             |                | Average Cylinder Pressure   | Average Temperature | Cp Average - Isooctane | Cp Average - Oxygen | Cp Average - Nitrogen | Cp Average Overall | Cv Average Overall |          |
| Degrees     | m <sup>3</sup> | Pascals                     | Kelvin              | KJ/Kmol.K              | KJ/Kmol.K           | KJ/Kmol.K             | KJ/Kmol.K          | KJ/Kmol.K          |          |
| -10         | 4.03E-05       | 3458300                     | 774.848             | 380.343                | 33.565              | 31.250                | 38.097             | 29.782             | 1.279    |
| -9          | 3.97E-05       | 3538466.7                   | 780.625             | 381.954                | 33.607              | 31.290                | 38.166             | 29.852             | 1.279    |
| -8          | 3.92E-05       | 3615266.7                   | 786.323             | 383.530                | 33.648              | 31.329                | 38.234             | 29.920             | 1.278    |
| -7          | 3.87E-05       | 3669800                     | 788.197             | 384.045                | 33.662              | 31.342                | 38.256             | 29.942             | 1.278    |
| -6          | 3.82E-05       | 3720666.7                   | 790.236             | 384.604                | 33.676              | 31.356                | 38.280             | 29.966             | 1.277    |
| -5          | 3.79E-05       | 3793433.3                   | 798.106             | 386.746                | 33.732              | 31.411                | 38.373             | 30.059             | 1.277    |
| -4          | 3.76E-05       | 3865100                     | 806.744             | 389.066                | 33.792              | 31.471                | 38.475             | 30.160             | 1.276    |
| -3          | 3.74E-05       | 3944466.7                   | 818.271             | 392.116                | 33.870              | 31.551                | 38.608             | 30.294             | 1.274    |
| -2          | 3.72E-05       | 3996900                     | 825.596             | 394.027                | 33.919              | 31.601                | 38.692             | 30.378             | 1.274    |
| -1          | 3.71E-05       | 4082500                     | 841.010             | 397.977                | 34.019              | 31.707                | 38.867             | 30.552             | 1.272    |
| 0           | 3.71E-05       | 4194766.7                   | 863.205             | 403.504                | 34.157              | 31.858                | 39.113             | 30.799             | 1.270    |
| 1           | 3.71E-05       | 4319666.7                   | 889.867             | 409.897                | 34.314              | 32.035                | 39.400             | 31.085             | 1.267    |
| 2           | 3.72E-05       | 4453833.3                   | 919.980             | 416.808                | 34.480              | 32.229                | 39.711             | 31.396             | 1.265    |
| 3           | 3.74E-05       | 4605033.3                   | 955.304             | 424.513                | 34.663              | 32.446                | 40.057             | 31.743             | 1.262    |
| 4           | 3.76E-05       | 4802266.7                   | 1002.354            | 434.141                | 34.888              | 32.711                | 40.485             | 32.170             | 1.258    |
| 5           | 3.79E-05       | 5030433.3                   | 1058.360            | 444.723                | 35.090              | 33.002                | 40.946             | 32.631             | 1.255    |
| 6           | 3.82E-05       | 5265966.7                   | 1118.444            | 455.113                | 35.300              | 33.298                | 41.407             | 33.093             | 1.251    |
| 7           | 3.87E-05       | 5530533.3                   | 1187.536            | 465.970                | 35.536              | 33.616                | 41.901             | 33.586             | 1.248    |
| 8           | 3.92E-05       | 5817433.3                   | 1264.973            | 476.952                | 35.791              | 33.947                | 42.410             | 34.096             | 1.244    |
| 9           | 3.97E-05       | 6129933.3                   | 1351.991            | 488.083                | 36.067              | 34.288                | 42.935             | 34.621             | 1.240    |
| 10          | 4.03E-05       | 6437633.3                   | 1442.024            | 498.600                | 36.342              | 34.610                | 43.434             | 35.119             | 1.237    |

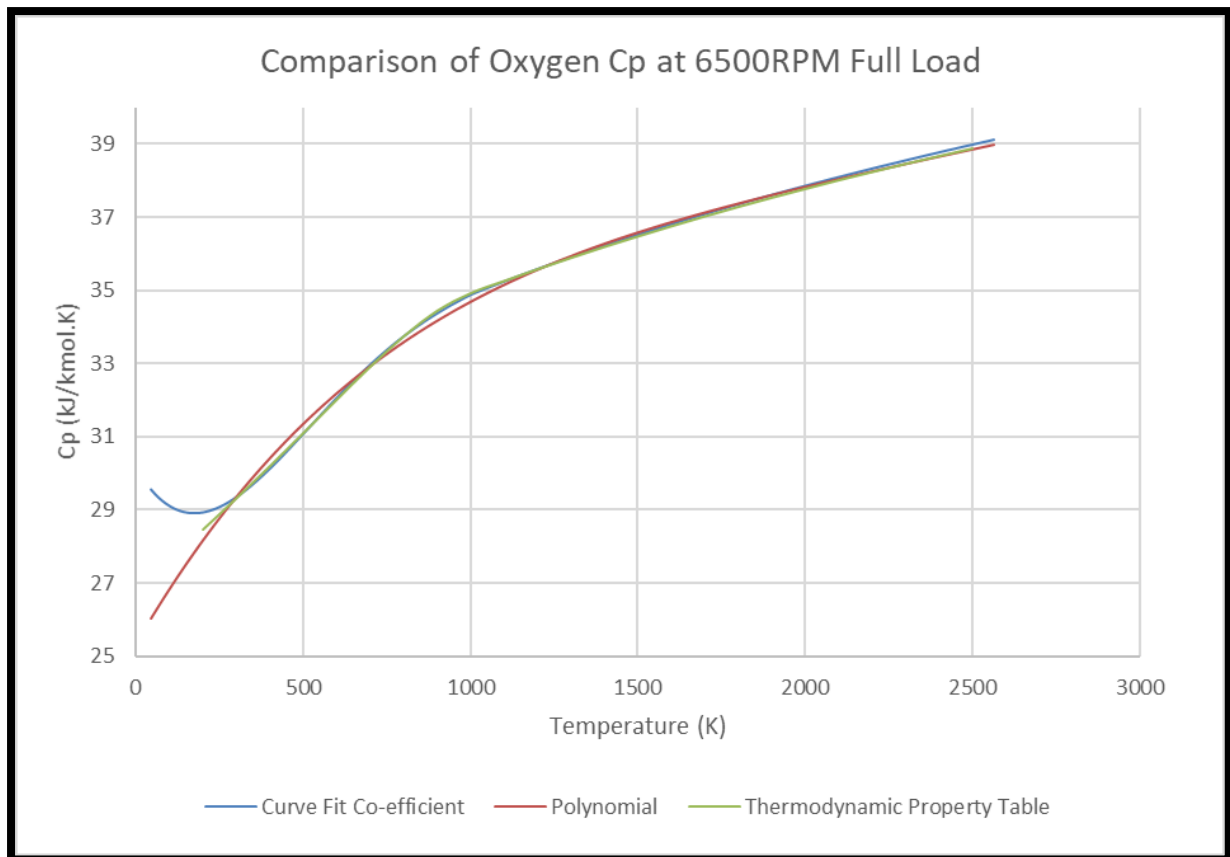


*Figure 20: Comparison of Oxygen Cp at 6500RPM Full Load*

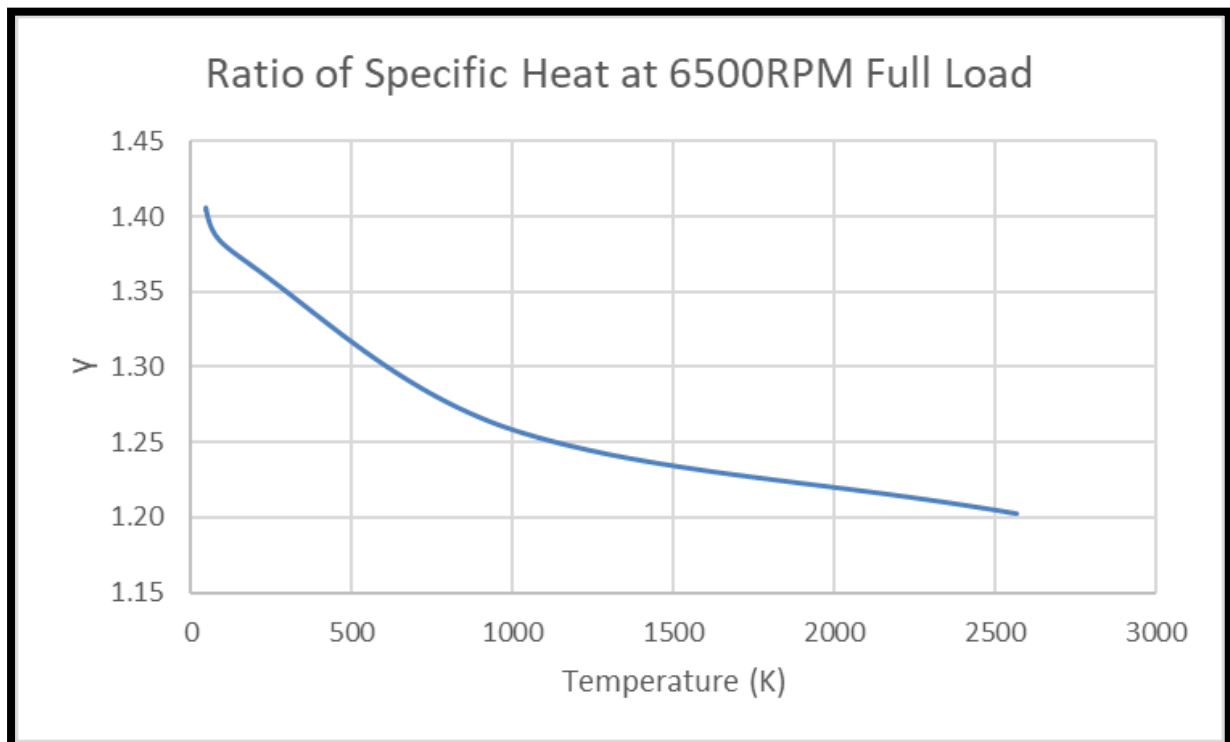


*Figure 21: Ratio of Specific Heat at 6500RPM Full Load*

## 4.2 Thermal Otto Cycle Efficiency

As with all efficiencies, the Otto cycle thermal efficiency is defined by the ratio of the work done over the heat supplied. The Otto cycle thermal efficiency is dependent of the compression ratio of the engine. This relationship and the derivation of the efficiency calculation (Equation 47) can be seen in the appendix.

$$\eta_{th} = 1 - \frac{1}{CR^{\gamma-1}}$$

*Equation 47: Thermal Efficiency using Compression Ratio (Heywood, 1988)*

The results of the Otto cycle thermal efficiency calculated using Equation 47 can be seen in the tables below. The two methods to obtain the ratio of specific heat that were covered in the previous section were used in the calculations. As the specific heats were calculated for the entire 720 degrees of data, the maximum values were used to calculate the ratio of specific heat and the thermal efficiency. As observed previously, the specific heat increases with temperature, and so by using the max values, the efficiency at the hottest point in the cycle can be obtained.

Table 51 shows the curve coefficient results at full load and Table 52 shows the results using the polynomial method. Comparing the table shows a slight difference in values, however it is so small it can be attributed to the calculation errors discussed previously. Both tables show that as the RPM is increased, the thermal efficiency reduces.

The results for the part load calculation can be seen in Table 53 and Table 54. As with the full load results, there is very little difference between the values from each method. The tables show that the load influences the efficiency. At 3000RPM, the efficiency at full load is lower than at 60%-part load. The highest efficiency at part load is shown to be at 10% load at 1500RPM, however this is not as efficient as at full load.

Table 51: Full Load Otto Thermal Efficiency using Curve Coefficient method

| Full Load - Otto Thermal Efficiency using Curve Coefficient Method |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |
|--------------------------------------------------------------------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|
|                                                                    | RPM    |        |        |        |        |        |        |        |        |        |        |        |        |        |        |
|                                                                    | 1000   | 1250   | 1500   | 1750   | 2000   | 2250   | 2500   | 3000   | 3500   | 4000   | 4500   | 5000   | 5500   | 6000   | 6500   |
| <b>Cp Max</b>                                                      | 44.561 | 44.405 | 44.440 | 45.950 | 47.105 | 47.409 | 47.720 | 48.359 | 49.507 | 48.006 | 48.257 | 48.875 | 48.909 | 49.072 | 49.264 |
| <b>Cv Max</b>                                                      | 36.246 | 36.090 | 36.126 | 37.636 | 38.790 | 39.095 | 39.405 | 40.044 | 41.193 | 39.691 | 39.943 | 40.561 | 40.594 | 40.757 | 40.950 |
| <b>γ</b>                                                           | 1.229  | 1.230  | 1.230  | 1.221  | 1.214  | 1.213  | 1.211  | 1.208  | 1.202  | 1.209  | 1.208  | 1.205  | 1.205  | 1.204  | 1.203  |
| <b>Efficiency using Cp&amp;Cv Max</b>                              | 41.03% | 41.17% | 41.14% | 39.87% | 38.95% | 38.72% | 38.48% | 38.00% | 37.17% | 38.27% | 38.08% | 37.62% | 37.60% | 37.48% | 37.34% |

Table 52: Full Load Otto Thermal Efficiency using Polynomial method

| Full Load - Otto Thermal Efficiency using Polynomial Method |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |
|-------------------------------------------------------------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|
|                                                             | RPM    |        |        |        |        |        |        |        |        |        |        |        |        |        |        |
|                                                             | 1000   | 1250   | 1500   | 1750   | 2000   | 2250   | 2500   | 3000   | 3500   | 4000   | 4500   | 5000   | 5500   | 6000   | 6500   |
| <b>Cp Max</b>                                               | 44.587 | 44.438 | 44.475 | 45.942 | 47.059 | 47.354 | 47.653 | 48.296 | 49.411 | 47.938 | 48.186 | 48.799 | 48.832 | 48.998 | 49.183 |
| <b>Cv Max</b>                                               | 36.273 | 36.123 | 36.160 | 37.627 | 38.744 | 39.040 | 39.338 | 39.981 | 41.097 | 39.623 | 39.871 | 40.485 | 40.518 | 40.683 | 40.869 |
| <b>γ</b>                                                    | 1.229  | 1.230  | 1.230  | 1.221  | 1.215  | 1.213  | 1.211  | 1.208  | 1.202  | 1.210  | 1.209  | 1.205  | 1.205  | 1.204  | 1.203  |
| <b>Efficiency using Cp&amp;Cv Max</b>                       | 41.01% | 41.14% | 41.11% | 39.88% | 38.99% | 38.76% | 38.53% | 38.05% | 37.24% | 38.32% | 38.13% | 37.68% | 37.66% | 37.54% | 37.40% |

Table 53: Part Load Otto Cycle Thermal Efficiency using Curve Coefficient method

| Part Load - Otto Thermal Efficiency using Curve Coefficient Method |        |        |        |        |        |        |        |
|--------------------------------------------------------------------|--------|--------|--------|--------|--------|--------|--------|
|                                                                    | RPM    |        |        |        |        |        |        |
|                                                                    | 800    | 1500   | 1500   | 2000   | 2500   | 3000   | 4000   |
| Load (%)                                                           | 5      | 10     | 20     | 30     | 20     | 60     | 30     |
| Cp Max                                                             | 47.811 | 46.085 | 47.876 | 48.707 | 48.020 | 47.879 | 48.937 |
| Cv Max                                                             | 39.497 | 37.770 | 39.561 | 40.393 | 39.706 | 39.564 | 40.622 |
| $\gamma$ Max                                                       | 1.211  | 1.220  | 1.210  | 1.206  | 1.209  | 1.210  | 1.205  |
| Efficiency using Cp&Cv Max                                         | 38.41% | 39.76% | 38.36% | 37.75% | 38.26% | 38.36% | 37.58% |

Table 54: Part Load Otto Thermal Efficiency using Polynomial method

| Part Load - Otto Thermal Efficiency using Polynomial Method |        |        |        |        |        |        |        |
|-------------------------------------------------------------|--------|--------|--------|--------|--------|--------|--------|
|                                                             | RPM    |        |        |        |        |        |        |
|                                                             | 800    | 1500   | 1500   | 2000   | 2500   | 3000   | 4000   |
| Load (%)                                                    | 5      | 10     | 20     | 30     | 20     | 60     | 30     |
| Cp Max                                                      | 47.738 | 46.076 | 47.797 | 48.611 | 47.938 | 47.801 | 48.837 |
| Cv Max                                                      | 39.424 | 37.762 | 39.482 | 40.296 | 39.623 | 39.486 | 40.522 |
| $\gamma$ Max                                                | 1.211  | 1.220  | 1.211  | 1.206  | 1.210  | 1.211  | 1.205  |
| Efficiency using Cp&Cv Max                                  | 38.47% | 39.77% | 38.42% | 37.82% | 38.32% | 38.42% | 37.65% |

### 4.3 Ideal Otto Cycle

Other than the initial values, the temperatures and pressures for the ideal Otto cycle are all based from calculation rather than data. The initial temperature was taken from the supplied intercooler out data. The initial pressure was assumed to be the pressure from BDC of the PV data supplied. The specific heats were calculated from this data using the same method as previously covered. The method used to find the remaining pressures and temperatures is detailed below.

To work out  $P_2$  the relationship shown in Equation 48 was used.

$$P_1 V_1^\gamma = P_2 V_2^\gamma$$

*Equation 48: Pressure-Volume Relationship (Colin R Ferguson, 2001)*

Equation 48 can then be rearranged to give Equation 49.

$$P_2 = P_1 \left( \frac{V_1}{V_2} \right)^\gamma$$

*Equation 49: P2 Calculation (Colin R Ferguson, 2001)*

This method is used to work out the pressures up to TDC where Equation 50 is used to find the pressure.

$$P_3 = P_2 \left( \frac{T_3}{T_2} \right)$$

*Equation 50: P3 Calculation (Colin R Ferguson, 2001)*

After TDC Equation 49 is continued to be used until BDC which is equal to  $P_1$ .

The pressure calculations require the ratio of specific heats. To find it at each degree the temperature needs to be calculated. However, as will be seen the temperature calculations also require the use of the ratio of specific heats. This was worked around by using the ratio of specific heat of the previous calculation as the pressure ( $P_1$ ) and temperature ( $T_1$ ) are already defined at BDC ( $V_1$ ), the difference between the ratio of specific heats in 1 degree is so minimal this had no effect on the results.

$T_2$  is found using the relationship shown in Equation 51 .

$$TV^{\gamma-1} = \text{Constant}$$

*Equation 51: Temperature-Volume Relationship (Urieli, 2018)*

This is rearranged to give Equation 52.

$$T_2 = T_1 \left( \frac{V_1}{V_2} \right)^{\gamma-1}$$

*Equation 52: T2 Calculation (Urieli, 2018)*

Equation 52 is used to calculate the temperature until TDC ( $T_3$ ), when there is the addition of heat from an external source. The temperature at  $T_3$  is found using

$$T_3 = T_2 + \left( \frac{Q_{in}}{AF_{Mass} \times C_v} \right)$$

Equation 53:  $T_3$  Calculation (Colin R Ferguson, 2001)

Where

$$Q_{in} = \text{Calorific Value} \times \text{Fuel Mass}$$

Equation 54:  $Q_{in}$  Calculation (Heywood, 1988)

And

$$C_v = \frac{\widetilde{C_v}}{\text{Molecular Weight Unburned}}$$

Equation 55:  $C_v$  Conversion (Heywood, 1988)

After TDC the use of Equation 52 is resumed until BDC.

$Q_{out}$  is the heat energy rejected from the cycle. It is calculated using Equation 56.

$$Q_{out} = AF \text{ Mass} \times C_v \times (T_4 - T_3)$$

Equation 56:  $Q_{out}$  Calculation (Heywood, 1988)

Figure 22 is an shows an Ideal Otto cycle graph calculated using the method above.

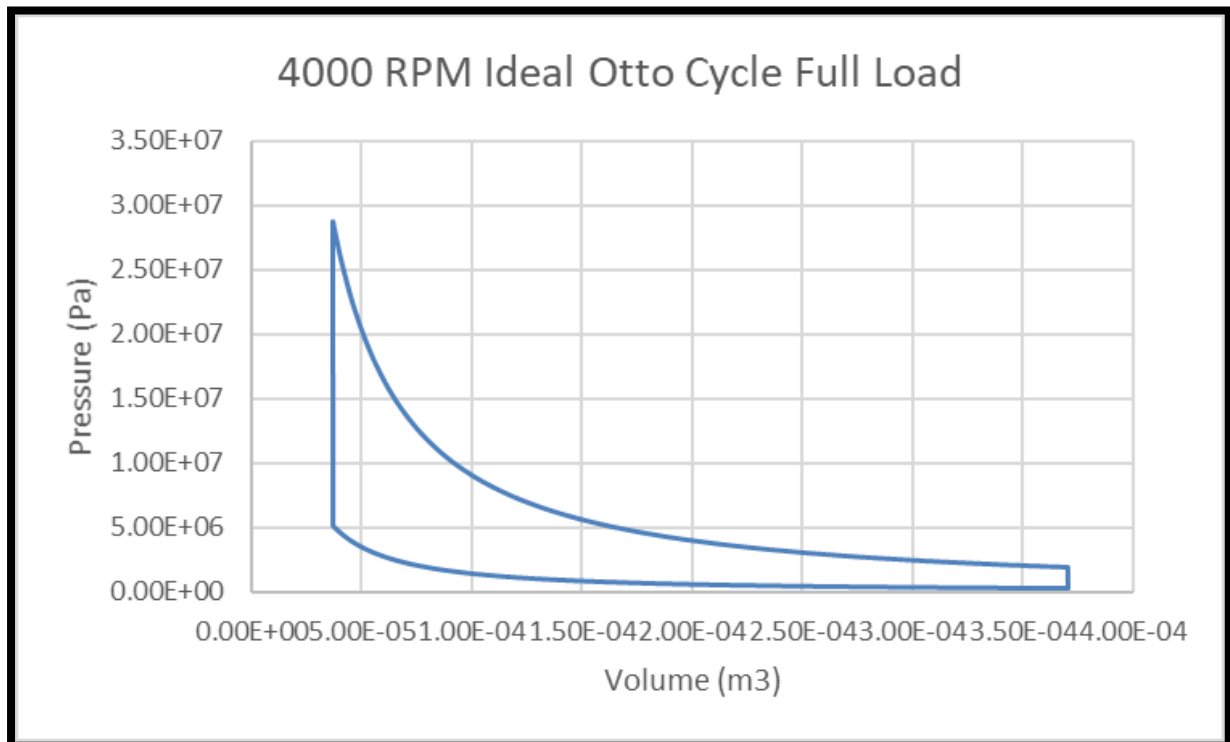


Figure 22: 4000RPM Ideal Otto Cycle Full Load

#### 4.4 Ideal Otto Cycle with variable CV and $\gamma$

The ideal Otto cycle can be calculated using the assumption that the  $C_v$  value at between  $T_2$  and  $T_3$  is fixed. This however is not the case, as the cycle experiences a massive increase in heat input. This results in a change in the  $C_v$  value and the heat output. The same method as the standard ideal Otto cycle is followed, however at TDC a different method is introduced to obtain  $T_3$ . An extract of the data calculations can be seen in Table 55 and the method is described below.

To calculate the value of  $T_3$ , a table was created that uses the increase of temperature by 1K to calculate the specific heats of the mixture rather than using the increase in volume and pressure to drive the calculations. The heat needed to increase the temperature by 1K ( $\delta Q$ ) can then be obtained using Equation 57 (Heywood, 1988). The sum of  $\delta Q$  is taken at each temperature until its value is equal to the of the  $Q_{in}$ . The temperature at which this occurs is  $T_3$ , an example of this is shown in Table 55.

$$\delta Q = AF \text{ Mass} \times C_v \times 1$$

Equation 57:  $dQ$  Calculation (Heywood, 1988)

Table 55: Extract of calculations for  $T_3$

| 1250                     |           |          |        |         |           |          |                             |                             |                  |
|--------------------------|-----------|----------|--------|---------|-----------|----------|-----------------------------|-----------------------------|------------------|
| Variable CV Calculations |           |          |        |         |           |          | Polynomial -<br>Variable CV | Coefficient-<br>Variable CV |                  |
| T2                       | Cp        |          |        |         | Cv        | CV       | dQ                          | Sum dQ for<br>T3            | Sum dQ for<br>T3 |
|                          | IsoOctane | Nitrogen | Oxygen | Mixture | Mixture   | Mixture  |                             |                             |                  |
|                          | KJ/Kmol.K |          |        |         | KJ/Kmol.K | J/Kg.K   |                             |                             |                  |
| 3325                     | 1138.930  | 37.183   | 40.408 | 57.952  | 49.637    | 1632.365 | 1.008                       | 2059.568                    | 2057.827         |
| 3326                     | 1139.800  | 37.184   | 40.409 | 57.968  | 49.654    | 1632.918 | 1.008                       | 2060.576                    | 2058.835         |
| 3327                     | 1140.672  | 37.185   | 40.411 | 57.985  | 49.671    | 1633.471 | 1.009                       | 2061.585                    | 2059.844         |
| 3328                     | 1141.545  | 37.185   | 40.413 | 58.002  | 49.688    | 1634.024 | 1.009                       | 2062.594                    | 2060.853         |
| 3329                     | 1142.418  | 37.186   | 40.415 | 58.019  | 49.704    | 1634.578 | 1.009                       | 2063.603                    | 2061.862         |
| 3330                     | 1143.292  | 37.187   | 40.416 | 58.036  | 49.721    | 1635.133 | 1.010                       | 2064.612                    | 2062.871         |
| 3331                     | 1144.167  | 37.187   | 40.418 | 58.053  | 49.738    | 1635.688 | 1.010                       | 2065.622                    | 2063.881         |
| 3332                     | 1145.044  | 37.188   | 40.420 | 58.070  | 49.755    | 1636.244 | 1.010                       | 2066.633                    | 2064.891         |
| 3333                     | 1145.921  | 37.189   | 40.422 | 58.086  | 49.772    | 1636.800 | 1.011                       | 2067.643                    | 2065.902         |
| 3334                     | 1146.798  | 37.190   | 40.423 | 58.103  | 49.789    | 1637.357 | 1.011                       | 2068.654                    | 2066.913         |
| 3335                     | 1147.677  | 37.190   | 40.425 | 58.120  | 49.806    | 1637.914 | 1.011                       | 2069.665                    | 2067.924         |
| 3336                     | 1148.557  | 37.191   | 40.427 | 58.137  | 49.823    | 1638.472 | 1.012                       | 2070.677                    | 2068.936         |
| 3337                     | 1149.437  | 37.192   | 40.429 | 58.154  | 49.840    | 1639.031 | 1.012                       | 2071.689                    | 2069.948         |
| 3338                     | 1150.319  | 37.192   | 40.430 | 58.171  | 49.857    | 1639.590 | 1.012                       |                             | 2070.960         |
| 3339                     | 1151.201  | 37.193   | 40.432 | 58.188  | 49.874    | 1640.149 | 1.013                       |                             | 2071.972         |

The value of  $T_3$  calculated from the table is then inputted into the ideal Otto cycle. The rest of the temperature values are calculated using the same method as the standard cycle.

The variable  $C_v$  also affects the  $Q_{out}$  value of the cycle. The  $Q_{out}$  can be obtained using the same method used to get  $T_3$ , however, rather than using the sum of  $\delta Q$  to work out the temperature from the  $Q_{in}$  value, a slightly different technique is used. To get the value of  $Q_{out}$ , the sum of  $\delta Q$  is calculated between  $T_1$  and  $T_4$ . An example of the  $Q_{out}$  calculations can be seen in Table 56.

Table 56: Extract of Variable Cv Calculations for Qout

| 1250                     |           |          |        |         |           |          |                             |                             |                      |
|--------------------------|-----------|----------|--------|---------|-----------|----------|-----------------------------|-----------------------------|----------------------|
| Variable CV Calculations |           |          |        |         |           |          | Polynomial -<br>Variable CV | Coefficient-<br>Variable CV |                      |
| T                        | Cp        |          |        |         | Cv        | CV       | dQ                          | Sum dQ from<br>T1-T4        | Sum dQ from<br>T1-T4 |
|                          | IsoOctane | Nitrogen | Oxygen | Mixture | Mixture   | Mixture  |                             |                             |                      |
|                          | KJ/Kmol.K |          |        |         | KJ/Kmol.K | J/Kg.K   |                             |                             |                      |
| 2054                     | 572.072   | 36.160   | 37.942 | 46.306  | 37.991    | 1249.387 | 0.771                       | 1152.769                    | 1152.769             |
| 2055                     | 572.232   | 36.161   | 37.944 | 46.310  | 37.996    | 1249.536 | 0.771                       | 1153.540                    | 1153.540             |
| 2056                     | 572.392   | 36.163   | 37.947 | 46.315  | 38.001    | 1249.684 | 0.772                       | 1154.312                    | 1154.312             |
| 2057                     | 572.552   | 36.164   | 37.949 | 46.320  | 38.005    | 1249.833 | 0.772                       | 1155.083                    | 1155.083             |
| 2058                     | 572.712   | 36.166   | 37.951 | 46.324  | 38.010    | 1249.982 | 0.772                       | 1155.855                    | 1155.855             |
| 2059                     | 572.873   | 36.167   | 37.953 | 46.329  | 38.014    | 1250.130 | 0.772                       | 1156.627                    | 1156.627             |
| 2060                     | 573.034   | 36.168   | 37.955 | 46.333  | 38.019    | 1250.279 | 0.772                       | 1157.399                    | 1157.399             |
| 2061                     | 573.195   | 36.170   | 37.957 | 46.338  | 38.023    | 1250.428 | 0.772                       |                             | 1158.171             |
| 2062                     | 573.356   | 36.171   | 37.959 | 46.342  | 38.028    | 1250.577 | 0.772                       |                             | 1158.943             |
| 2063                     | 573.518   | 36.173   | 37.962 | 46.347  | 38.032    | 1250.726 | 0.772                       |                             | 1159.715             |
| 2064                     | 573.680   | 36.174   | 37.964 | 46.351  | 38.037    | 1250.875 | 0.772                       |                             | 1160.487             |

#### 4.5 Ideal Otto Cycle with fixed $\gamma$

The ideal Otto cycle can be calculated using the assumption that the specific heat ratios of expansion and compression are constant. For expansion,  $\gamma$  is assumed to be 1.2 and 1.3 for compression. To calculate T3 and the Qout of this cycle follows the same steps as the variable  $\widetilde{Cv}$ .

## 4.6 Ideal Otto Cycle Temperature Results

Table 57: Full Load Ideal Otto Cycle Temperature Results

| RPM  | T1(Kelvin) | T2(Kelvin) |             |                 | T3(Kelvin)          |                        |                                     |                                      |                 | T4(Kelvin)          |                        |                                     |                                      |                 |
|------|------------|------------|-------------|-----------------|---------------------|------------------------|-------------------------------------|--------------------------------------|-----------------|---------------------|------------------------|-------------------------------------|--------------------------------------|-----------------|
|      |            | Polynomial | Coefficient | Fixed $\lambda$ | Standard-Polynomial | Standard - Coefficient | Variable CV & $\lambda$ -Polynomial | Variable CV & $\lambda$ -Coefficient | Fixed $\lambda$ | Standard-Polynomial | Standard - Coefficient | Variable CV & $\lambda$ -Polynomial | Variable CV & $\lambda$ -Coefficient | Fixed $\lambda$ |
| 1000 | 298        | 641.70     | 644.03      | 594.38          | 3522.28             | 3537.75                | 2825                                | 2827                                 | 2795            | 2211.76             | 2226.85                | 1684.26                             | 1685.88                              | 1763.37         |
| 1250 | 312.8      | 668.80     | 671.44      | 623.90          | 3688.62             | 3701.53                | 3337                                | 3339                                 | 3312            | 2353.82             | 2367.45                | 2060.83                             | 2064.21                              | 2089.55         |
| 1500 | 313.1      | 671.42     | 671.42      | 624.49          | 3545.48             | 3545.48                | 3721                                | 3721                                 | 3698            | 2235.45             | 2235.45                | 2388.10                             | 2388.10                              | 2333.08         |
| 1750 | 313.1      | 663.94     | 666.51      | 624.49          | 3708.16             | 3721.46                | 3862                                | 3864                                 | 3844            | 2402.67             | 2416.95                | 2547.08                             | 2550.96                              | 2425.19         |
| 2000 | 313        | 661.58     | 664.11      | 661.58          | 3766.83             | 3780.52                | 3967                                | 3968                                 | 3967            | 2470.06             | 2485.01                | 2665.68                             | 2668.39                              | 2665.68         |
| 2250 | 313.3      | 661.64     | 664.17      | 624.89          | 3754.03             | 3767.64                | 3971                                | 3973                                 | 3955            | 2460.93             | 2475.77                | 2673.07                             | 2676.79                              | 2495.22         |
| 2500 | 313        | 661.39     | 663.92      | 624.29          | 3761.78             | 3775.46                | 3981                                | 3982                                 | 3965            | 2466.47             | 2481.40                | 2681.25                             | 2683.94                              | 2501.53         |
| 3000 | 313.1      | 656.58     | 659.04      | 624.49          | 3629.07             | 3642.58                | 3870                                | 3871                                 | 3855            | 2372.42             | 2386.86                | 2602.88                             | 2605.68                              | 2432.13         |
| 3500 | 313.1      | 658.10     | 660.58      | 624.49          | 3669.53             | 3683.09                | 3704                                | 3704                                 | 3699            | 2401.01             | 2415.61                | 2433.00                             | 2435.05                              | 2333.71         |
| 4000 | 313.4      | 660.45     | 662.96      | 625.09          | 3717.74             | 3731.29                | 3774                                | 3775                                 | 3757            | 2435.15             | 2449.85                | 2488.11                             | 2491.07                              | 2370.30         |
| 4500 | 313.2      | 659.19     | 661.69      | 624.69          | 3693.91             | 3707.48                | 3562                                | 3563                                 | 3544            | 2418.26             | 2432.93                | 2298.91                             | 2301.88                              | 2235.92         |
| 5000 | 323.4      | 674.35     | 676.97      | 645.04          | 3616.57             | 3627.94                | 3515                                | 3516                                 | 3500            | 2362.78             | 2375.23                | 2271.94                             | 2274.85                              | 2208.16         |
| 5500 | 323.4      | 674.24     | 676.86      | 645.04          | 3613.72             | 3625.08                | 3397                                | 3398                                 | 3381            | 2360.78             | 2373.21                | 2170.95                             | 2173.69                              | 2133.08         |
| 6000 | 323.2      | 672.19     | 674.78      | 644.64          | 3570.15             | 3581.55                | 3227                                | 3229                                 | 3190            | 2330.19             | 2342.54                | 2038.56                             | 2041.71                              | 2012.58         |
| 6500 | 323.2      | 672.71     | 675.31      | 644.64          | 3583.41             | 3594.81                | 2908                                | 2910                                 | 2889            | 2339.49             | 2351.88                | 1792.01                             | 1794.05                              | 1822.68         |

Table 58: Part Load Ideal Otto Cycle Temperature Results

| RPM  | Load(%) | T1(Kelvin) | T2(Kelvin) |             |                 | T3(Kelvin)          |                        |                                     |                                      |                 | T4(Kelvin)          |                        |                                     |                                      |                 |
|------|---------|------------|------------|-------------|-----------------|---------------------|------------------------|-------------------------------------|--------------------------------------|-----------------|---------------------|------------------------|-------------------------------------|--------------------------------------|-----------------|
|      |         |            | Polynomial | Coefficient | Fixed $\lambda$ | Standard-Polynomial | Standard - Coefficient | Variable CV & $\lambda$ -Polynomial | Variable CV & $\lambda$ -Coefficient | Fixed $\lambda$ | Standard-Polynomial | Standard - Coefficient | Variable CV & $\lambda$ -Polynomial | Variable CV & $\lambda$ -Coefficient | Fixed $\lambda$ |
| 800  | 5       | 296.8      | 633.03     | 635.23      | 591.98          | 3776.96             | 3794.22                | 3044.00                             | 3046.00                              | 3018.00         | 2476.43             | 2494.76                | 1866.02                             | 1868.49                              | 1904.06         |
| 1500 | 10      | 298.4      | 636.53     | 638.78      | 595.17          | 3751.86             | 3768.62                | 3028.00                             | 3029.00                              | 3011.00         | 2451.21             | 2468.94                | 1853.55                             | 1855.22                              | 1902.01         |
| 1500 | 20      | 299        | 637.84     | 640.10      | 596.37          | 2414.95             | 2425.39                | 2105.00                             | 2108.00                              | 2075.00         | 1423.29             | 1429.63                | 1218.65                             | 1220.11                              | 1309.12         |
| 2000 | 30      | 299.5      | 638.69     | 640.97      | 597.37          | 3744.45             | 3760.93                | 3024.00                             | 3025.00                              | 2998.00         | 2440.94             | 2458.34                | 1848.05                             | 1849.70                              | 1891.45         |
| 2500 | 20      | 299        | 637.88     | 640.14      | 596.37          | 3741.30             | 3757.87                | 3021.00                             | 3023.00                              | 2995.00         | 2437.46             | 2454.93                | 1845.49                             | 1847.87                              | 1889.55         |
| 3000 | 60      | 301        | 641.31     | 643.62      | 600.36          | 3747.10             | 3763.27                | 3029.00                             | 3030.00                              | 3003.00         | 2443.95             | 2461.09                | 1852.09                             | 1853.76                              | 1894.60         |
| 4000 | 30      | 300.1      | 639.69     | 641.97      | 598.57          | 3747.56             | 3763.93                | 3027.00                             | 3029.00                              | 3001.00         | 2444.38             | 2461.70                | 1850.61                             | 1853.01                              | 1893.34         |

The results of the temperature calculations for each of the variations of the ideal Otto cycle can be seen for full load in Table 57 and for part load in Table 58. When comparing the results from the 2 methods of finding the specific heats, a difference between the results can be seen, although small. It can also be seen that the temperature from the cycles calculated using the variable  $C_v$  are significantly lower than those that used the standard method. The temperatures at T1 and T2 do not increase much with RPM. The differences in temperature become obvious after the input of heat at T3. At full load the temperature increases with RPM until it peaks at 2500RPM, it then begins to reduce again to 6500RPM. T4 shows the same pattern with the highest temperature being at 2500RPM. Looking at the part load temperatures, the same trend as full load at T1 and T2 is present. Different loads do not seem to have much effect on temperatures. There is an anomaly at 20% load at 1500RPM, this has been attributed to a calculation error.

#### 4.7 Ideal Otto Cycle Pressure Results

Looking at the results of the ideal Otto cycle pressure calculations at full load, it is possible to see that they follow the same patterns as the temperature results. This is due to the dependence of temperature and pressure on each other for the calculations. At part load, as the load increases, so does the pressure. When comparing the pressure results at part load to the temperatures at part load, it appears that the pressure is affected more by the loading of the engine.

Table 59: Full Load Ideal Otto Cycle Pressure Results

| RPM  | P1 & P4    | P2         |             |                 | P3                  |                        |                                     |                                      |                 |
|------|------------|------------|-------------|-----------------|---------------------|------------------------|-------------------------------------|--------------------------------------|-----------------|
|      |            | Polynomial | Coefficient | Fixed $\lambda$ | Standard-Polynomial | Standard - Coefficient | Variable CV & $\lambda$ -Polynomial | Variable CV & $\lambda$ -Coefficient | Fixed $\lambda$ |
| 1000 | 132100     | 2841220    | 2851508     | 2631677         | 15595346            | 15663827               | 12508047                            | 12516902                             | 12375218        |
| 1250 | 170133.333 | 3633304    | 3647658     | 3389372         | 20038796            | 20108886               | 18128562                            | 18139427                             | 17992747        |
| 1500 | 194933.333 | 4175228    | 4175228     | 3883434         | 22047672            | 22047672               | 23139139                            | 23139139                             | 22996113        |
| 1750 | 213400     | 4519869    | 4537342     | 4251324         | 25243761            | 25334295               | 26291061                            | 26304676                             | 26168523        |
| 2000 | 238933.33  | 5044298    | 5063605     | 5044298         | 28720589            | 28824939               | 30246776                            | 30254401                             | 30246776        |
| 2250 | 245200     | 5172082    | 5191863     | 4884840         | 29345537            | 29451909               | 31041625                            | 31057259                             | 30916552        |
| 2500 | 255300     | 5388274    | 5408881     | 5086050         | 30646771            | 30758232               | 32432703                            | 32440850                             | 32302353        |
| 3000 | 253866.667 | 5317346    | 5337242     | 5057496         | 29390186            | 29499598               | 31341377                            | 31349475                             | 31219898        |
| 3500 | 252333.333 | 5297448    | 5317405     | 5026949         | 29538331            | 29647497               | 29815838                            | 29815838                             | 29775590        |
| 4000 | 242933.333 | 5113425    | 5132873     | 4839683         | 28784034            | 28888949               | 29219616                            | 29227358                             | 29087996        |
| 4500 | 233733.333 | 4913559    | 4932155     | 4656402         | 27534010            | 27635149               | 26550781                            | 26558235                             | 26416611        |
| 5000 | 246733.333 | 5138778    | 5158743     | 4915386         | 27559352            | 27645983               | 26785369                            | 26792989                             | 26671064        |
| 5500 | 240633.333 | 5010905    | 5030364     | 4793863         | 26856797            | 26941283               | 25246188                            | 25253620                             | 25127277        |
| 6000 | 219166.667 | 4552838    | 4570385     | 4366207         | 24181000            | 24258208               | 21856801                            | 21870348                             | 21606197        |
| 6500 | 183466.667 | 3814150    | 3828881     | 3654997         | 20317329            | 20381982               | 16487876                            | 16499216                             | 16380149        |

Table 60: Part Load Ideal Otto Cycle Pressure Results

| RPM  | Load(%) | P1 & P4  | P2         |             |                 | P3                  |                        |                                     |                                      |                 |
|------|---------|----------|------------|-------------|-----------------|---------------------|------------------------|-------------------------------------|--------------------------------------|-----------------|
|      |         |          | Polynomial | Coefficient | Fixed $\lambda$ | Standard-Polynomial | Standard - Coefficient | Variable CV & $\lambda$ -Polynomial | Variable CV & $\lambda$ -Coefficient | Fixed $\lambda$ |
| 800  | 5       | 3185.01  | 67851.18   | 68086.57    | 63451.32        | 404831.23           | 406680.73              | 326269.17                           | 326483.54                            | 323482.38       |
| 1500 | 10      | 34191.90 | 728502.74  | 731070.56   | 681166.17       | 4293939.50          | 4313120.39             | 3465491.00                          | 3466635.49                           | 3446034.81      |
| 1500 | 20      | 53275.90 | 1135150.38 | 1139174.40  | 1061354.90      | 4297857.22          | 4316442.14             | 3746245.17                          | 3751584.24                           | 3692854.50      |
| 2000 | 30      | 67814.78 | 1444459.90 | 1449598.42  | 1350996.40      | 8468380.38          | 8505646.95             | 6839018.94                          | 6841280.52                           | 6780217.85      |
| 2500 | 20      | 49578.69 | 1056446.12 | 1060191.98  | 987699.61       | 6196276.93          | 6223714.59             | 5003329.14                          | 5006641.50                           | 4960268.38      |
| 3000 | 60      | 85028.83 | 1809477.67 | 1815981.91  | 1693932.26      | 10572556.04         | 10618179.94            | 8546405.01                          | 8549226.54                           | 8473045.31      |
| 4000 | 30      | 72197.61 | 1537129.31 | 1542619.17  | 1438310.52      | 9005129.66          | 9044459.12             | 7273672.38                          | 7278478.24                           | 7211196.17      |

#### 4.8 Ideal Otto Cycle Efficiency

As with the other thermal efficiencies discussed during the study, the efficiency of the ideal Otto cycle is based off Equation 58.

$$\eta_{th} = \frac{\text{Work}}{\text{Heat input}}$$

Equation 58: Thermal Efficiency Definition (Nuclear Power, 2018)

This can be rewritten as Equation 59.

$$\eta_{th} = 1 - \frac{Q_{out}}{Q_{in}}$$

Equation 59: Ideal Otto Cycle Thermal Efficiency (Nuclear Power, 2018)

The values of  $Q_{in}$ ,  $Q_{out}$  and the cycle efficiency at full load can be seen in Table 61 and at part load in Table 62.

The values of  $Q_{in}$  at full load increase with RPM until they reach a peak at 2500RPM, the values then begin to gradually reduce until 6500RPM. The  $Q_{in}$  values of the part load data increases with RPM as well as load.

The patterns seen in the  $Q_{in}$  values when compared to RPM are also reflected in the  $Q_{out}$  values. Comparing the differences between the 2 methods of working out the specific heats for the standard ideal Otto cycle, there are slight differences, with the curve coefficient method showing a higher  $Q_{out}$  value than the polynomial method. This is true at both full load and part load. When comparing the standard ideal Otto cycle to the cycle using the variable  $C_v$  at full load it can be seen there is a large difference in the values, with the variable  $C_v$  cycle having a lower value of  $Q_{out}$ . The difference between values of difference specific heat calculations is smaller in the variable  $C_v$  cycle than the standard cycle, however the coefficient still shows higher values of  $Q_{out}$  than the polynomial method other than at 1000RPM. At full load, the cycle using the fixed  $\gamma$  values has a higher  $Q_{out}$  at 1000,1250 and 6500RPM, however at the rest of the RPMs both the standard and variable  $C_v$  cycles have larger  $Q_{out}$  values. At

part load, the fixed  $\gamma$  cycle has higher values of  $Q_{out}$  than the variable cycle but lower values than the standard cycle.

The efficiency values at full load decrease as the RPM increases, with the highest efficiency being at 1000 RPM other than for the fixed  $\gamma$  cycle. The value at 1250RPM for the standard cycles does not follow the trend and show a lower efficiency than the other RPMS. Comparing the curve coefficient and polynomial methods there is very little difference in efficiency for both the standard cycles and the variable  $C_v$  cycles. At the lower RPMs the cycle calculated using the variable  $C_v$  is up to 2.5% more efficient than the standard cycle, however as RPM increases the difference in efficiency between the cycles is less than 0.5%. The fixed  $\gamma$  method is the least efficient at 1000RPM and 6500, however in between the 2 RPMs the efficiency improves, with a peak efficiency of 46.86% at 2000RPM. At part load the difference between the standard cycle and the variable  $C_v$  cycle is more defined, with the showing higher values throughout the RPM range. The efficiency at 1500RPM 20% load is high and is attributed to a calculation error. The fixed  $\gamma$  cycle shows a relatively constant value of efficiency through the range of RPMS.

Table 61: Full Load Ideal Otto Cycle Efficiency

| RPM  | Q <sub>in</sub> (Joules) | Q <sub>out</sub> (Joules) |                        |                          |                           |         | η(%)                |                        |                          |                           |         |
|------|--------------------------|---------------------------|------------------------|--------------------------|---------------------------|---------|---------------------|------------------------|--------------------------|---------------------------|---------|
|      |                          | Standard-Polynomial       | Standard - Coefficient | Variable CV - Polynomial | Variable CV - Coefficient | Fixed λ | Standard-Polynomial | Standard - Coefficient | Variable CV - Polynomial | Variable CV - Coefficient | Fixed λ |
| 1000 | 1607.45                  | 906.93                    | 918.42                 | 885.38                   | 874.20                    | 938.82  | 43.58               | 42.86                  | 44.92                    | 45.62                     | 41.60   |
| 1250 | 2071.83                  | 1259.57                   | 1271.32                | 1157.40                  | 1160.49                   | 1179.82 | 39.20               | 38.64                  | 44.14                    | 43.99                     | 43.05   |
| 1500 | 2487.25                  | 1413.62                   | 1417.29                | 1415.45                  | 1415.45                   | 1371.30 | 43.17               | 43.02                  | 43.09                    | 43.09                     | 44.87   |
| 1750 | 2662.07                  | 1543.04                   | 1557.58                | 1545.24                  | 1547.72                   | 1445.36 | 42.04               | 41.49                  | 41.95                    | 41.86                     | 45.71   |
| 2000 | 2796.69                  | 1638.48                   | 1654.08                | 1643.88                  | 1646.42                   | 1486.05 | 41.41               | 40.86                  | 41.22                    | 41.13                     | 46.86   |
| 2250 | 2802.61                  | 1641.03                   | 1656.56                | 1650.65                  | 1653.19                   | 1502.42 | 41.45               | 40.89                  | 41.10                    | 41.01                     | 46.39   |
| 2500 | 2815.88                  | 1649.37                   | 1665.08                | 1657.43                  | 1659.13                   | 1506.52 | 41.43               | 40.87                  | 41.14                    | 41.08                     | 46.50   |
| 3000 | 2675.81                  | 1558.79                   | 1573.71                | 1590.95                  | 1593.46                   | 1451.04 | 41.74               | 41.19                  | 40.54                    | 40.45                     | 45.77   |
| 3500 | 2474.41                  | 1443.83                   | 1457.63                | 1451.85                  | 1453.47                   | 1371.30 | 41.65               | 41.09                  | 41.33                    | 41.26                     | 44.58   |
| 4000 | 2556.80                  | 1494.84                   | 1508.99                | 1496.69                  | 1499.14                   | 1400.96 | 41.53               | 40.98                  | 41.46                    | 41.37                     | 45.21   |
| 4500 | 2314.77                  | 1352.03                   | 1364.90                | 1343.38                  | 1345.77                   | 1293.47 | 41.59               | 41.04                  | 41.96                    | 41.86                     | 44.12   |
| 5000 | 2254.29                  | 1311.96                   | 1321.60                | 1317.08                  | 1319.46                   | 1267.34 | 41.80               | 41.37                  | 41.57                    | 41.47                     | 43.78   |
| 5500 | 2129.79                  | 1239.36                   | 1248.47                | 1237.54                  | 1239.89                   | 1208.66 | 41.81               | 41.38                  | 41.89                    | 41.78                     | 43.25   |
| 6000 | 1960.96                  | 1139.21                   | 1147.66                | 1135.09                  | 1137.40                   | 1115.10 | 41.91               | 41.47                  | 42.12                    | 42.00                     | 43.13   |
| 6500 | 1662.10                  | 966.08                    | 973.24                 | 948.38                   | 949.88                    | 1016.07 | 41.88               | 41.45                  | 42.94                    | 42.85                     | 38.87   |

Table 62: Part Load Ideal Otto Cycle Efficiency

| RPM  | Load(%) | Q <sub>in</sub> (Joules) | Q <sub>out</sub> (Joules) |                        |                             |                              |         | η(%)                |                        |                             |                              |         |
|------|---------|--------------------------|---------------------------|------------------------|-----------------------------|------------------------------|---------|---------------------|------------------------|-----------------------------|------------------------------|---------|
|      |         |                          | Standard-Polynomial       | Standard - Coefficient | Variable CV & λ- Polynomial | Variable CV & λ- Coefficient | Fixed λ | Standard-Polynomial | Standard - Coefficient | Variable CV & λ- Polynomial | Variable CV & λ- Coefficient | Fixed λ |
| 800  | 5       | 223.2570253              | 130.91                    | 132.66                 | 126.03                      | 126.22                       | 129.58  | 41.36               | 40.58                  | 43.55                       | 43.46                        | 41.96   |
| 1500 | 10      | 257.9858959              | 150.81                    | 152.75                 | 145.46                      | 145.68                       | 150.80  | 41.54               | 40.79                  | 43.62                       | 43.53                        | 41.55   |
| 1500 | 20      | 208.3732236              | 111.44                    | 112.57                 | 112.12                      | 112.40                       | 124.97  | 46.52               | 45.97                  | 46.19                       | 46.06                        | 40.03   |
| 2000 | 30      | 466.3591195              | 271.99                    | 275.42                 | 262.54                      | 262.73                       | 270.95  | 41.68               | 40.94                  | 43.71                       | 43.66                        | 41.90   |
| 2500 | 20      | 365.149268               | 212.86                    | 215.57                 | 205.37                      | 205.68                       | 212.17  | 41.71               | 40.96                  | 43.76                       | 43.67                        | 41.89   |
| 3000 | 60      | 785.5339779              | 458.32                    | 463.94                 | 442.52                      | 444.18                       | 456.46  | 41.66               | 40.94                  | 43.67                       | 43.46                        | 41.89   |
| 4000 | 30      | 591.631117               | 345.22                    | 349.53                 | 332.95                      | 333.70                       | 343.70  | 41.65               | 40.92                  | 43.72                       | 43.60                        | 41.91   |

## 5 Conclusion

The first part of the report calculates the thermochemistry of combustion from the supplied Ford data. From this it was learnt how much the AFR effects the characteristics of the engine as most of the calculations used throughout the study are directly affected by the AFR and how the possibility of improvement by modification is present. If less fuel is used, then the engine will be more efficient, therefore, if the AFR of the engine was modified to run leaner, the efficiency of the engine would be improved. There is currently research being undertaken to improve the efficiency of internal combustion engines to over 50% using ultra-lean combustion (Yamamoto, 1999). High performance Formula 1 engines have achieved over 50% thermal efficiency in dyno tests using pre-chamber technology, which allows an ultra-lean combustion (Perkins, 2017).

The turbulent flame speeds of the engine were then investigated. It was seen that as the RPM increased, as did the flame speeds because of the rise in turbulence. The speed of combustion has a role in the efficiency of the engine. A slow combustion can create inefficiency as there is the chance that not all the fuel in the cylinder will be combusted before the exhaust valve opens. To try and prevent this the spark timing of the engine will be advanced. The combustion then begins before the piston reaches TDC resulting in resistance caused by the rise in pressure from combustion. Conversely to this, a fast combustion means the spark timing can be retarded closer to TDC resulting in a better efficiency (Rockett Brand Racing Fuel, 2018).

This study also covered different methods of calculating the thermal efficiency of the engine. The calculation of the specific heats was required to be able to work out the Otto cycle efficiencies. 2 methods were discovered that could be used to calculate the specific heats, one using the polynomials from the thermodynamic properties table, the other using curve coefficient equations. It was found that the methods provided different results, however only marginally. It is reasonable to assume that if the polynomials were further expanded, the results would eventually intercept. There is also a small margin of error with big polynomials that could cause large differences in calculations. 4 different methods of calculating the Otto cycle efficiency were investigated in the study. A comparison between the methods can be seen in Table 63 and Table 64 and in Figure 23. The tables show that all the methods provide similar results. The two methods that provide the most similar results are the standard Otto cycle and the variable Cv Otto cycle. The main difference between the calculations is that at T3 the variable Cv calculated the change in temperature between V2 and V3, whereas the standard cycle assumes it remains constant. The compression ratio Otto cycle is shown to have the lowest of the Otto cycle efficiencies. The max values of specific heats were used to calculate the ratio of specific heat, by using these figures the value of the ratio of specific heats was around 1.2. Further

investigation is required to ascertain if there is a better way to obtain the values of specific heat or if the max values for the cycle provide the best efficiency.

Table 63: Summary of Calculated Efficiencies Full Load

| RPM  | Compression Ratio |             | Standard Ideal Otto Cycle |             | Variable Cv Otto Cycle |             | Fixed $\gamma$ Otto Cycle | Actual Cycle             |                              |
|------|-------------------|-------------|---------------------------|-------------|------------------------|-------------|---------------------------|--------------------------|------------------------------|
|      | Polynomial        | Coefficient | Polynomial                | Coefficient | Polynomial             | Coefficient |                           | Brake Thermal Efficiency | Indicated Thermal Efficiency |
| 1000 | 41.01             | 41.03       | 43.58                     | 42.86       | 44.92                  | 45.62       | 41.60                     | 28.03                    | 30.38                        |
| 1250 | 41.14             | 41.17       | 39.20                     | 38.64       | 44.14                  | 43.99       | 43.05                     | 28.22                    | 30.14                        |
| 1500 | 41.11             | 41.14       | 43.17                     | 43.02       | 43.09                  | 43.09       | 44.87                     | 28.16                    | 29.86                        |
| 1750 | 39.88             | 39.87       | 42.04                     | 41.49       | 41.95                  | 41.86       | 45.71                     | 29.07                    | 30.84                        |
| 2000 | 38.99             | 38.95       | 41.41                     | 40.86       | 41.22                  | 41.13       | 46.86                     | 29.68                    | 31.55                        |
| 2250 | 38.76             | 38.72       | 41.45                     | 40.89       | 41.10                  | 41.01       | 46.39                     | 29.91                    | 31.96                        |
| 2500 | 38.53             | 38.48       | 41.43                     | 40.87       | 41.14                  | 41.08       | 46.50                     | 29.86                    | 32.03                        |
| 3000 | 38.05             | 38.00       | 41.74                     | 41.19       | 40.54                  | 40.45       | 45.77                     | 31.67                    | 33.52                        |
| 3500 | 37.24             | 37.17       | 41.65                     | 41.09       | 41.33                  | 41.26       | 44.58                     | 31.39                    | 33.92                        |
| 4000 | 38.32             | 38.27       | 41.53                     | 40.98       | 41.46                  | 41.37       | 45.21                     | 30.84                    | 33.26                        |
| 4500 | 38.13             | 38.08       | 41.59                     | 41.04       | 41.96                  | 41.86       | 44.12                     | 31.64                    | 34.29                        |
| 5000 | 37.68             | 37.62       | 41.80                     | 41.37       | 41.57                  | 41.47       | 43.78                     | 30.79                    | 33.60                        |
| 5500 | 37.66             | 37.60       | 41.81                     | 41.38       | 41.89                  | 41.78       | 43.25                     | 30.75                    | 33.90                        |
| 6000 | 37.54             | 37.48       | 41.91                     | 41.47       | 42.12                  | 42.00       | 43.13                     | 31.30                    | 34.54                        |
| 6500 | 37.40             | 37.34       | 41.88                     | 41.45       | 42.94                  | 42.85       | 38.87                     | 31.78                    | 35.92                        |

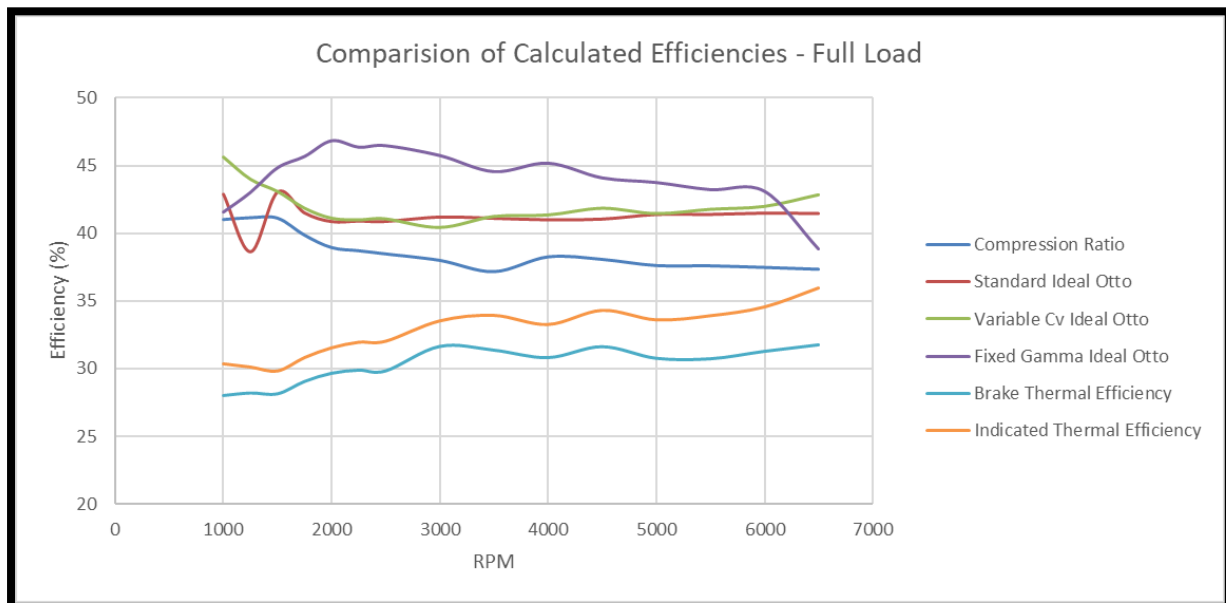


Figure 23: Comparison of Calculated Efficiencies

Table 64: Summary of Calculated Efficiencies Part Load

| RPM   | Load (%) | Compression Ratio |             | Standard Ideal Otto Cycle |             | Variable Cv Otto Cycle |             | Fixed $\gamma$ Otto Cycle | Actual Cycle             |                              |
|-------|----------|-------------------|-------------|---------------------------|-------------|------------------------|-------------|---------------------------|--------------------------|------------------------------|
|       |          | Polynomial        | Coefficient | Polynomial                | Coefficient | Polynomial             | Coefficient |                           | Brake Thermal Efficiency | Indicated Thermal Efficiency |
| 800.1 | 5        | 38.47             | 38.41       | 41.36                     | 40.58       | 43.55                  | 43.46       | 41.96                     | 10.56                    | 21.01                        |
| 1500  | 10       | 39.77             | 39.76       | 41.54                     | 40.79       | 43.62                  | 43.53       | 41.55                     | 15.64                    | 21.99                        |
| 1500  | 20       | 38.42             | 38.36       | 46.52                     | 45.97       | 46.19                  | 46.06       | 40.03                     | 22.13                    | 30.75                        |
| 2000  | 30       | 37.82             | 37.75       | 41.68                     | 40.94       | 43.71                  | 43.66       | 41.90                     | 26.79                    | 34.30                        |
| 2500  | 20       | 38.32             | 38.26       | 41.71                     | 40.96       | 43.76                  | 43.67       | 41.89                     | 22.79                    | 31.27                        |
| 3000  | 60       | 38.42             | 38.36       | 41.66                     | 40.94       | 43.67                  | 43.46       | 41.89                     | 31.01                    | 34.97                        |
| 4000  | 40       | 37.65             | 37.58       | 41.65                     | 40.92       | 43.72                  | 43.60       | 41.91                     | 26.10                    | 45.51                        |

The actual cycle efficiencies of the engine were calculated using the BMEP from test data of the engine and the work done obtained from the PV data. When comparing the actual cycle to the ideal Otto cycles it is evident the ideal cycles have efficiencies over 10% higher. This is particularly obvious in Figure 24. These differences can be attributed to multiple factors. The ideal cycles do not consider heat transfer, in the actual cycle heat transfer causes the pressure to reduce below the level of the ideal cycle. The combustion in the ideal cycles is instant, however in reality this is not the case. Combustion is commencing before TDC and continues after it as the volume is increasing, meaning less pressure and a lower peak, this is sometimes referred to as time losses. In the actual cycle, the exhaust valve is opened before BDC to exhaust the combustion products. These blowdown losses cause the pressure to reduced further below that of the ideal cycle (Heywood, 1988).

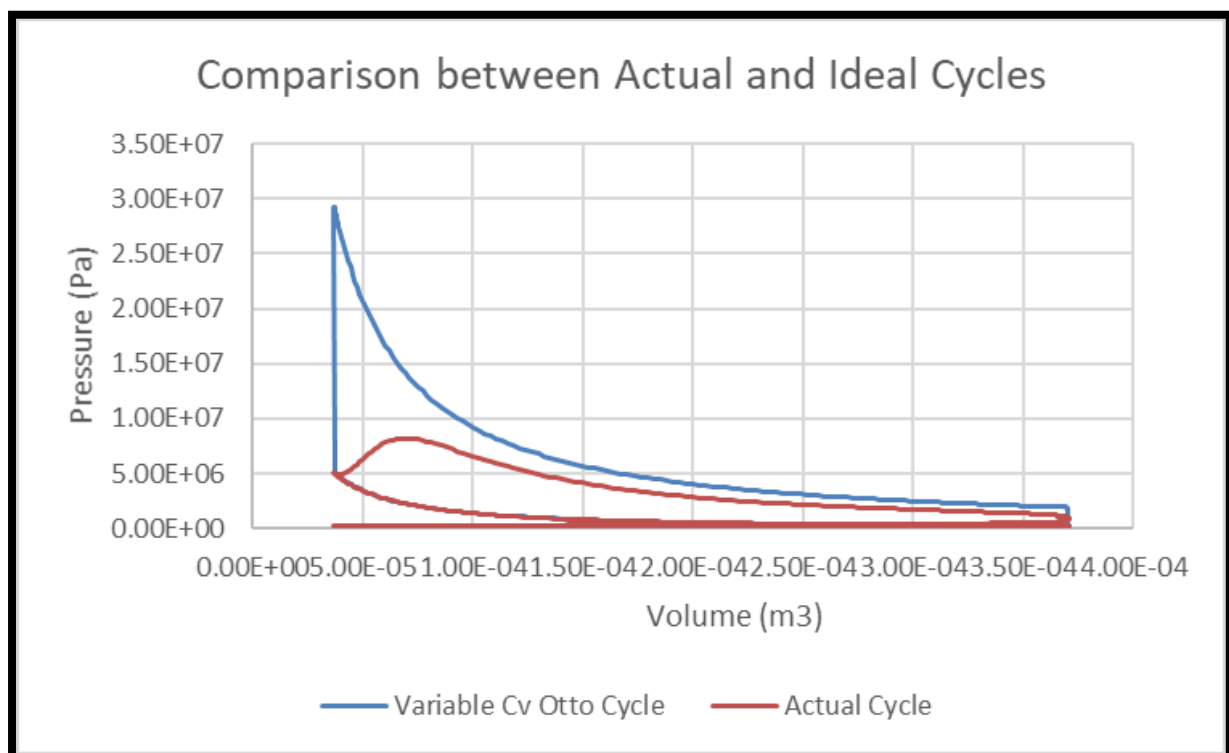


Figure 24: Comparison between Actual and Ideal Cycles at 4000RPM Full Load

As part of the study, the losses of fuel energy down the exhaust were examined. Table 65 and Table 66 show comparisons of the fuel energy lost down the exhaust, the brake thermal efficiency and the other energy losses. The other losses attributed to the inefficiencies previously discussed. As the engine is turbocharged, losses in the compressor and turbines can also be considered (Heywood, 1988). The tables show that the fuel losses and thermal efficiency increase with RPM, lowering the other losses. The engine is turbocharged, therefore, some of the energy lost down the exhaust is recovered by the turbo and used to power the compressor.

Table 65: Fuel Energy Distribution Full Load

| RPM  | Fuel Energy Lost<br>Down Exhaust | Brake Thermal<br>Efficiency | Other Losses | Total Energy<br>Lost | Fuel Energy<br>Supplied | Fuel Energy<br>Used | Fuel Energy<br>Lost |
|------|----------------------------------|-----------------------------|--------------|----------------------|-------------------------|---------------------|---------------------|
|      | %                                | %                           | %            | %                    | KJ/s                    | KJ/s                | KJ/s                |
| 1000 | 24.11                            | 28.03                       | 47.86        | 71.97                | 40.19                   | 11.27               | 28.92               |
| 1250 | 27.46                            | 28.22                       | 44.32        | 71.78                | 64.74                   | 18.27               | 46.47               |
| 1500 | 30.00                            | 28.16                       | 41.84        | 71.84                | 93.27                   | 26.27               | 67.01               |
| 1750 | 31.79                            | 29.07                       | 39.13        | 70.93                | 116.47                  | 33.86               | 82.60               |
| 2000 | 34.48                            | 29.68                       | 35.84        | 70.32                | 139.83                  | 41.50               | 98.34               |
| 2250 | 35.79                            | 29.91                       | 34.30        | 70.09                | 157.65                  | 47.15               | 110.49              |
| 2500 | 37.46                            | 29.86                       | 32.68        | 70.14                | 175.99                  | 52.55               | 123.45              |
| 3000 | 39.51                            | 31.67                       | 28.83        | 68.33                | 200.69                  | 63.55               | 137.14              |
| 3500 | 40.03                            | 31.39                       | 28.59        | 68.61                | 216.51                  | 67.96               | 148.55              |
| 4000 | 40.67                            | 30.84                       | 28.49        | 69.16                | 255.68                  | 78.84               | 176.84              |
| 4500 | 40.60                            | 31.64                       | 27.76        | 68.36                | 260.41                  | 82.41               | 178.01              |
| 5000 | 42.83                            | 30.79                       | 26.38        | 69.21                | 281.79                  | 86.76               | 195.03              |
| 5500 | 42.89                            | 30.75                       | 26.36        | 69.25                | 292.85                  | 90.05               | 202.79              |
| 6000 | 42.74                            | 31.30                       | 25.96        | 68.70                | 294.14                  | 92.07               | 202.08              |
| 6500 | 40.86                            | 31.78                       | 27.35        | 68.22                | 270.09                  | 85.85               | 184.24              |

Table 66: Fuel Energy Distribution Part Load

| RPM   | Load (%) | Fuel Energy Lost<br>Down Exhaust | Brake Thermal<br>Efficiency | Other Losses | Total Energy<br>Lost | Fuel Energy<br>Supplied | Fuel Energy<br>Used | Fuel Energy<br>Lost |
|-------|----------|----------------------------------|-----------------------------|--------------|----------------------|-------------------------|---------------------|---------------------|
|       |          | %                                | %                           | %            | %                    | KJ/s                    | KJ/s                | KJ/s                |
| 800.1 | 5        | 8.70                             | 10.56                       | 80.73        | 89.44                | 4.47                    | 0.47                | 3.99                |
| 1500  | 10       | 17.05                            | 15.64                       | 67.31        | 84.36                | 9.67                    | 1.51                | 8.16                |
| 1500  | 20       | 17.96                            | 22.13                       | 59.92        | 77.87                | 13.64                   | 3.02                | 10.62               |
| 2000  | 30       | 20.35                            | 26.79                       | 52.86        | 73.21                | 23.32                   | 6.25                | 17.07               |
| 2500  | 20       | 22.27                            | 22.79                       | 54.94        | 77.21                | 22.82                   | 5.20                | 17.62               |
| 3000  | 60       | 27.61                            | 31.01                       | 41.38        | 68.99                | 58.92                   | 18.27               | 40.65               |
| 4000  | 40       | 28.85                            | 26.10                       | 45.05        | 73.90                | 59.16                   | 15.44               | 43.72               |

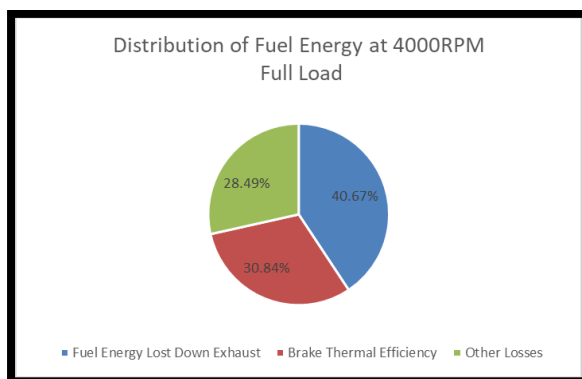


Figure 25: Distribution of Fuel Energy at 4000RPM Full Load

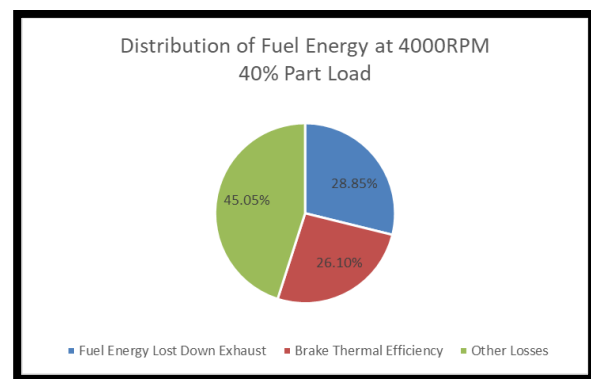


Figure 26: Distribution of Fuel Energy at 4000RPM Part Load

In conclusion, the study has shown that the efficiency of the engine is affected by many factors. The investigation showed the theoretical efficiencies of the engine are all in the region of 40%, however, the actual efficiencies are at least 10% lower. From this it can be taken that there is plenty of room for improvement. High end sport engines are currently running brake thermal efficiencies of above 50% which is an increase of over 20% from the brake thermal efficiency of the Ford Fox. Further study into the improvement of the calculated efficiencies through methods such as water injection and EGR would be the next phase of this project.

## 6 Appendix

### 6.1 Engine Specifications

Table 67: Ford Fox 1 Litre Engine Specification

|                       |      |                 |
|-----------------------|------|-----------------|
| Number of Cylinders   | 3    |                 |
| Compression Ratio     | 10:1 |                 |
| Engine Displacement   | 999  | cm <sup>3</sup> |
| Cylinder Displacement | 333  | cm <sup>3</sup> |
| Cylinder Bore         | 71.9 | mm              |
| Stroke                | 82   | mm              |

### 6.2 Otto Cycle Definition

The Otto cycle is a thermodynamic cycle that many engines function around. It operates using the 4 processes described below (Sankararaj, 2018). The descriptions refer to Figure 26 which shows a labelled example of an Otto cycle:

- **Isentropic compression (1-2)** - The piston travels from BDC to TDC causing the air in the cylinder to experience adiabatic compression that is reversible. The volume decreases from  $V_1$  to  $V_2$ , the pressure in the cylinder increases from  $P_1$  to  $P_2$  and the temperature also rises from  $T_1$  to  $T_2$ . This process is isentropic as the entropy remains constant throughout.
- **Isochoric Heat Addition (2-3)** -The piston remains at TDC as heat is added from an external source, in an engine this will be the spark plug resulting in combustion. As volume remains constant the process is isochoric, therefore  $V_2=V_3$ . The cylinder pressure increases from  $P_2$  to  $P_3$ . The temperature increases from  $T_2$  to  $T_3$ . The entropy is also increased.
- **Isentropic Expansion (3-4)** – As the piston moves from TDC to BDC the air in the cylinder undergoes reversible expansion. The volume increases from  $V_3$  to  $V_4$ . The pressure reduces from  $P_3$  to  $P_4$  and the temperature is reduced from  $T_3$  to  $T_4$ . The entropy remains constant.
- **Isochoric Heat Rejection (4-1)** -The piston remains at BDC therefore  $V_4=V_1$ . The pressure falls from  $P_4$  to  $P_1$  and the temperature is reduced from  $T_4$  to  $T_1$ . Entropy also reduces.

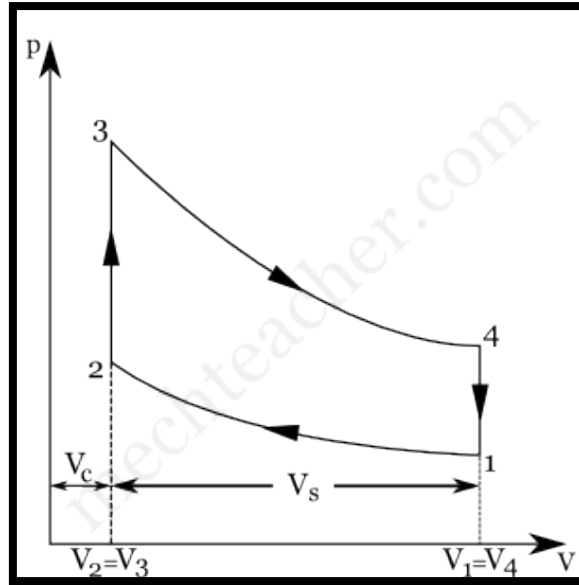


Figure 27: Example of Ideal Otto Cycle (Sankararaj, 2018)

### 6.3 Otto Cycle Thermal Efficiency Derivation

The heat supplied to the system during the isochoric heat addition phase of the Otto cycle (2-3) can be seen in Equation 60.

$$MCv(T_3 - T_2)$$

Equation 60: Heat Supplied to Otto Cycle (Sankararaj, 2018)

The heat ejected from the system during the isochoric heat rejection phase of the Otto cycle (4-1) can be seen in Equation 61.

$$MCv(T_4 - T_1)$$

Equation 61: Heat Rejected from Otto Cycle (Sankararaj, 2018)

The thermal efficiency of the Otto cycle is Equation 62, using Equation 60 and Equation 61, this can be written as Equation 63.

$$\eta_{th} = \frac{\text{Heat Supplied} - \text{Heat Rejected}}{\text{Heat Supplied}}$$

Equation 62: Thermal Efficiency of Otto Cycle Definition (Sankararaj, 2018)

$$\eta_{th} = \frac{MCv(T_3 - T_2) - MCv(T_4 - T_1)}{MCv(T_3 - T_2)}$$

Equation 63: Thermal Efficiency of Otto Cycle 1 (Sankararaj, 2018)

Equation 63 can be rearranged to Equation 64:

$$\eta_{th} = 1 - \frac{T_4 - T_1}{T_3 - T_2}$$

*Equation 64: Thermal Efficiency of Otto Cycle 2 (Sankararaj, 2018)*

As the processes between 1-2 and 3-4 are assumed to be isentropic and take place between the same volumes  $V_1=V_4$  and  $V_2=V_3$ , the relationships between  $T_2$  and  $T_1$  and also between  $T_3$  and  $T_4$  can be expressed as Equation 65.

$$\frac{T_2}{T_1} = \left(\frac{V_1}{V_2}\right)^{\gamma-1} = CR^{\gamma-1} = \frac{T_3}{T_4} = \left(\frac{V_4}{V_3}\right)^{\gamma-1}$$

*Equation 65: Relationships of Temperature, Volume and Compression Ratio (Heywood, 1988)*

This rearranges to Equation 66.

$$\eta_{th} = 1 - \frac{1}{CR^{\gamma-1}}$$

*Equation 66: Thermal Efficiency using Compression Ratio*

## 6.4 Thermodynamic Property Tables (Turns, 2006)

| NASA Tables |                |             |                |             |           |             |                  |             |                 |             |
|-------------|----------------|-------------|----------------|-------------|-----------|-------------|------------------|-------------|-----------------|-------------|
| Temperature | O <sub>2</sub> |             | N <sub>2</sub> |             | CO        |             | H <sub>2</sub> O |             | CO <sub>2</sub> |             |
|             | Cp             | H(T)-H(298) | Cp             | H(T)-H(298) | Cp        | H(T)-H(298) | Cp               | H(T)-H(298) | Cp              | H(T)-H(298) |
| Kelvin      | kJ/kmol.K      | MJ/kmol     | kJ/kmol.K      | MJ/kmol     | kJ/kmol.K | MJ/kmol     | kJ/kmol.K        | MJ/kmol     | kJ/kmol.K       | MJ/kmol     |
| 200         | 28.473         | -2.836      | 28.793         | -2.841      | 28.687    | -2.835      | 32.255           | -3.227      | 32.387          | -3.423      |
| 298         | 29.315         | 0           | 29.071         | 0           | 29.072    | 0           | 33.448           | 0           | 37.198          | 0           |
| 300         | 29.331         | 0.054       | 29.075         | 0.054       | 29.078    | 0.054       | 33.468           | 0.062       | 37.28           | 0.069       |
| 400         | 30.21          | 3.031       | 29.319         | 2.973       | 29.433    | 2.979       | 34.437           | 3.458       | 41.276          | 4.003       |
| 500         | 31.114         | 6.097       | 29.636         | 5.92        | 29.857    | 5.943       | 35.337           | 6.947       | 44.569          | 8.301       |
| 600         | 32.03          | 9.254       | 30.086         | 8.905       | 30.407    | 8.955       | 36.288           | 10.528      | 47.313          | 12.899      |
| 700         | 32.927         | 12.503      | 30.684         | 11.942      | 31.089    | 12.029      | 37.364           | 14.209      | 49.617          | 17.749      |
| 800         | 33.757         | 15.838      | 31.394         | 15.046      | 31.86     | 15.176      | 38.587           | 18.005      | 51.55           | 22.81       |
| 900         | 34.454         | 19.25       | 32.131         | 18.222      | 32.629    | 18.401      | 39.93            | 21.93       | 53.136          | 28.047      |
| 1000        | 34.936         | 22.721      | 32.762         | 21.468      | 33.255    | 21.697      | 41.315           | 25.993      | 54.36           | 33.425      |
| 1100        | 35.27          | 26.232      | 33.258         | 24.77       | 33.725    | 25.046      | 42.638           | 30.1911     | 55.333          | 38.911      |
| 1200        | 35.593         | 29.775      | 33.707         | 28.118      | 34.148    | 28.44       | 43.874           | 34.518      | 56.205          | 44.488      |
| 1300        | 35.903         | 33.35       | 34.113         | 31.51       | 34.53     | 31.874      | 45.027           | 38.963      | 56.984          | 50.149      |
| 1400        | 36.202         | 36.955      | 34.477         | 34.939      | 34.872    | 35.345      | 46.102           | 43.52       | 57.677          | 55.882      |
| 1500        | 36.49          | 40.59       | 34.805         | 38.404      | 35.178    | 38.847      | 47.103           | 48.181      | 58.292          | 61.681      |
| 1600        | 36.768         | 44.253      | 35.099         | 41.899      | 35.451    | 42.379      | 48.035           | 52.939      | 58.836          | 67.538      |
| 1700        | 37.036         | 47.943      | 35.361         | 45.423      | 35.694    | 45.937      | 48.901           | 57.786      | 59.316          | 73.446      |
| 1800        | 37.296         | 51.66       | 35.595         | 48.971      | 35.91     | 49.517      | 49.705           | 62.717      | 59.738          | 79.399      |
| 1900        | 37.546         | 55.402      | 35.803         | 52.541      | 36.101    | 53.118      | 50.451           | 67.725      | 60.108          | 85.392      |
| 2000        | 37.788         | 59.169      | 35.988         | 56.13       | 36.271    | 56.737      | 51.143           | 72.805      | 60.433          | 91.42       |
| 2100        | 38.023         | 62.959      | 36.152         | 59.738      | 36.421    | 60.371      | 51.784           | 77.952      | 60.717          | 97.477      |
| 2200        | 38.25          | 66.773      | 36.298         | 63.36       | 36.553    | 64.02       | 52.378           | 83.16       | 60.966          | 103.562     |
| 2300        | 38.47          | 70.609      | 36.428         | 66.997      | 36.67     | 67.682      | 52.927           | 88.426      | 61.185          | 109.67      |
| 2400        | 38.684         | 74.467      | 36.543         | 70.645      | 36.774    | 71.354      | 53.435           | 93.744      | 61.378          | 115.798     |
| 2500        | 38.891         | 78.346      | 36.645         | 74.305      | 36.867    | 75.036      | 53.905           | 99.112      | 61.548          | 121.944     |
| 2600        | 39.093         | 82.245      | 36.737         | 77.974      | 36.95     | 78.727      | 54.34            | 104.524     | 61.701          | 128.107     |
| 2700        | 39.289         | 86.164      | 36.82          | 81.652      | 37.025    | 82.426      | 54.742           | 109.979     | 61.839          | 134.284     |
| 2800        | 39.48          | 90.103      | 36.895         | 85.338      | 37.093    | 86.132      | 55.115           | 115.472     | 61.965          | 140.474     |
| 2900        | 39.665         | 94.06       | 36.964         | 89.031      | 37.155    | 89.844      | 55.459           | 121.001     | 62.083          | 146.677     |
| 3000        | 39.846         | 98.036      | 37.028         | 92.73       | 37.213    | 93.562      | 55.779           | 126.563     | 62.194          | 152.891     |
| 3100        | 40.023         | 102.029     | 37.088         | 96.436      | 37.268    | 97.287      | 56.076           | 132.156     | 62.301          | 159.116     |
| 3200        | 40.195         | 106.04      | 37.144         | 100.148     | 37.321    | 101.016     | 56.353           | 137.777     | 62.406          | 165.351     |
| 3300        | 40.362         | 110.068     | 37.198         | 103.865     | 37.372    | 104.751     | 56.61            | 143.426     | 62.51           | 171.597     |
| 3400        | 40.526         | 114.112     | 37.251         | 107.587     | 37.422    | 108.49      | 56.851           | 149.099     | 62.614          | 177.853     |
| 3500        | 40.686         | 118.173     | 37.302         | 111.315     | 37.471    | 112.235     | 57.076           | 154.795     | 62.718          | 184.12      |
| 3600        | 40.842         | 122.249     | 37.352         | 115.048     | 37.521    | 115.985     | 57.288           | 160.514     | 62.825          | 190.397     |
| 3700        | 40.994         | 126.341     | 37.402         | 118.786     | 37.57     | 119.739     | 57.488           | 166.252     | 62.932          | 196.685     |
| 3800        | 41.143         | 130.448     | 37.452         | 122.528     | 37.619    | 123.499     | 57.676           | 172.011     | 63.041          | 202.983     |
| 3900        | 41.287         | 134.57      | 37.501         | 126.276     | 37.667    | 127.263     | 57.856           | 177.787     | 63.151          | 209.293     |
| 4000        | 41.429         | 138.705     | 37.549         | 130.028     | 37.716    | 131.032     | 58.026           | 183.582     | 63.261          | 215.613     |
| 4100        | 41.566         | 142.855     | 37.597         | 133.786     | 37.764    | 134.806     | 58.19            | 189.392     | 63.369          | 221.945     |
| 4200        | 41.7           | 147.019     | 37.643         | 137.548     | 37.81     | 138.585     | 58.346           | 195.219     | 63.474          | 228.287     |
| 4300        | 41.83          | 151.195     | 37.688         | 141.314     | 37.855    | 142.368     | 58.496           | 201.061     | 63.575          | 234.64      |
| 4400        | 41.957         | 155.384     | 37.73          | 145.085     | 37.897    | 146.156     | 58.641           | 206.918     | 63.669          | 241.002     |
| 4500        | 42.079         | 159.586     | 37.768         | 148.86      | 37.936    | 149.948     | 58.781           | 212.79      | 63.753          | 247.373     |
| 4600        | 42.197         | 163.8       | 37.803         | 152.639     | 37.97     | 153.743     | 58.916           | 218.674     | 63.825          | 253.752     |
| 4700        | 42.312         | 168.026     | 37.832         | 156.42      | 37.998    | 157.541     | 59.047           | 224.573     | 63.881          | 260.138     |
| 4800        | 42.421         | 172.262     | 37.854         | 160.205     | 38.019    | 161.342     | 59.173           | 230.484     | 63.918          | 266.528     |
| 4900        | 42.527         | 176.51      | 37.868         | 163.991     | 38.031    | 165.145     | 59.295           | 236.407     | 63.932          | 272.92      |
| 5000        | 42.627         | 180.767     | 37.873         | 167.778     | 38.033    | 168.948     | 59.412           | 242.343     | 63.919          | 279.313     |

## 6.5 Molecular Thermodynamic Properties (Heywood, 1988), (Turns, 2006)

| Molecule        | Symbol                         | Molecular Weight (g/Mol) | Enthalpy of Formation MJ/Kmol | Temperature Range | a <sub>1</sub> | a <sub>2</sub> | a <sub>3</sub> | a <sub>4</sub> | a <sub>5</sub> |
|-----------------|--------------------------------|--------------------------|-------------------------------|-------------------|----------------|----------------|----------------|----------------|----------------|
|                 |                                |                          |                               | Kelvin            |                |                |                |                |                |
| Carbon Dioxide  | CO <sub>2</sub>                | 44.011                   | 393.52                        | 1000-5000         | 4.4608         | 0.0030982      | -1.2393E-06    | 2.2741E-10     | -1.5526E-14    |
|                 |                                |                          |                               | 300-1000          | 2.4008         | 0.0087351      | -6.6071E-06    | 2.0022E-09     | 6.3274E-16     |
| Water           | H <sub>2</sub> O               | 18.016                   | 241.83                        | 1000-5000         | 2.7168         | 0.0029451      | -8.0224E-07    | 1.0227E-10     | -4.8472E-15    |
|                 |                                |                          |                               | 300-1000          | 4.0701         | -0.0011084     | 4.1521E-06     | -2.9637E-09    | 8.0702E-13     |
| Carbon Monoxide | CO                             | 28.01                    | 110.54                        | 1000-5000         | 2.9841         | 0.0014891      | -5.79E-07      | 1.0365E-10     | -6.9354E-15    |
|                 |                                |                          |                               | 300-1000          | 3.7101         | -0.0016191     | 3.6924E-06     | -2.032E-09     | 2.3953E-13     |
| Hydrogen        | H <sub>2</sub>                 | 2.016                    | 0                             | 1000-5000         | 3.1002         | 0.00051119     | 5.2644E-08     | -3.491E-11     | 3.6945E-15     |
|                 |                                |                          |                               | 300-1000          | 3.0574         | 0.0026765      | -5.8099E-06    | 5.521E-09      | -1.8123E-12    |
| Oxygen          | O <sub>2</sub>                 | 31.998                   | 0                             | 1000-5000         | 3.622          | 0.00073618     | -1.9652E-07    | 3.6202E-11     | -2.8946E-15    |
|                 |                                |                          |                               | 300-1000          | 3.6256         | -0.0018782     | 7.0555E-06     | -6.7635E-09    | 2.1556E-12     |
| Nitrogen        | N <sub>2</sub>                 | 28.013                   | 0                             | 1000-5000         | 2.8963         | 0.0015155      | -5.7235E-07    | 9.9807E-11     | -6.5224E-15    |
|                 |                                |                          |                               | 300-1000          | 3.6748         | -0.0012082     | 0.000002324    | -6.3218E-10    | -2.2577E-13    |
| Nitrogen Oxide  | NO                             |                          |                               | 1000-5000         | 3.189          | 0.0013382      | -5.2899E-07    | 9.5919E-11     | -6.4848E-15    |
| Oxygen          | O                              | 15.999                   | 0                             | 1000-5000         | 2.5421         | -2.7551E-05    | -3.1028E-09    | 4.5511E-12     | -4.3681E-16    |
| Hydrogen        | H                              | 1.008                    | 0                             | 1000-5000         | 2.5            | 0              | 0              | 0              | 0              |
| Carbon          | C                              | 12.011                   | 0                             |                   |                |                |                |                |                |
| Isooctane       | C <sub>8</sub> H <sub>18</sub> | 114.23                   | -224.1                        |                   | -0.55313       | 181.62         | -97.787        | 20.402         | -0.03095       |

## 6.6 Ford Engine Test Data

Table 68: Test Data Air:Fuel Ratio

| Air:Fuel Ratio in Cylinder | RPM   |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |
|----------------------------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
|                            | 800   | 1000  | 1250  | 1500  | 1750  | 2000  | 2250  | 2500  | 3000  | 3500  | 4000  | 4500  | 5000  | 5500  | 6000  | 6500  |
| FL                         |       | 16.15 | 16.19 | 16.05 | 14.92 | 14.45 | 14.35 | 14.41 | 13.42 | 13.71 | 14.07 | 13.89 | 13.36 | 13.34 | 13.04 | 13.13 |
| 200                        |       |       |       |       |       | 14.45 | 14.29 | 14.42 | 13.78 | 14.41 |       |       |       |       |       |       |
| 190                        |       |       |       |       |       | 14.42 | 14.37 | 14.42 | 13.56 | 13.95 |       |       |       |       |       |       |
| 180                        |       |       |       |       | 14.89 | 14.43 | 14.45 | 14.41 | 14.03 | 13.79 | 14.05 |       |       |       |       |       |
| 170                        |       |       |       | 16.05 | 15.50 | 14.45 | 14.46 | 14.43 | 14.45 | 13.67 | 14.26 | 13.91 |       |       |       |       |
| 160                        |       |       |       | 16.11 | 15.62 | 14.52 | 14.49 | 14.42 | 14.46 | 14.45 | 14.44 | 13.99 | 13.52 |       |       |       |
| 150                        |       |       |       | 16.19 | 15.74 | 14.57 | 14.52 | 14.42 | 14.46 | 14.46 | 14.46 | 14.20 | 13.95 | 13.62 |       |       |
| 140                        |       |       | 16.09 | 16.08 | 15.77 | 14.58 | 14.55 | 14.49 | 14.49 | 14.45 | 14.46 | 14.47 | 14.36 | 13.92 | 13.27 |       |
| 130                        |       |       | 15.95 | 16.02 | 15.59 | 14.62 | 14.57 | 14.57 | 14.56 | 14.43 | 14.45 | 14.47 | 14.51 | 14.03 | 13.57 |       |
| 120                        |       |       | 15.88 | 15.57 | 14.73 | 14.68 | 14.62 | 14.60 | 14.60 | 14.43 | 14.46 | 14.52 | 14.52 | 14.27 | 13.77 | 13.50 |
| 110                        |       | 15.91 | 15.87 | 15.42 | 14.76 | 14.73 | 14.66 | 14.61 | 14.61 | 14.47 | 14.50 | 14.55 | 14.53 | 14.52 | 13.94 | 13.80 |
| 100                        |       | 14.94 | 15.68 | 14.75 | 14.80 | 14.74 | 14.65 | 14.62 | 14.62 | 14.59 | 14.59 | 14.61 | 14.58 | 14.56 | 14.39 | 13.81 |
| 90                         |       | 14.84 | 15.34 | 14.79 | 14.76 | 14.68 | 14.63 | 14.65 | 14.65 | 14.63 | 14.65 | 14.67 | 14.63 | 14.62 | 14.58 | 14.55 |
| 80                         |       | 14.75 | 14.71 | 14.73 | 14.70 | 14.68 | 14.67 | 14.67 | 14.68 | 14.68 | 14.69 | 14.72 | 14.67 | 14.64 | 14.63 | 14.60 |
| 70                         |       | 14.72 | 14.72 | 14.72 | 14.72 | 14.71 | 14.70 | 14.70 | 14.71 | 14.69 | 14.70 | 14.71 | 14.67 | 14.67 | 14.64 | 14.61 |
| 60                         |       | 14.72 | 14.73 | 14.72 | 14.71 | 14.70 | 14.70 | 14.72 | 14.72 | 14.71 | 14.70 | 14.69 | 14.68 | 14.67 | 14.66 | 14.62 |
| 50                         |       | 14.74 | 14.73 | 14.75 | 14.74 | 14.69 | 14.70 | 14.73 | 14.73 | 14.71 | 14.71 | 14.71 | 14.69 | 14.69 | 14.69 | 14.65 |
| 40                         | 14.63 | 14.76 | 14.76 | 14.74 | 14.73 | 14.72 | 14.72 | 14.74 | 14.73 | 14.73 | 14.72 | 14.72 | 14.70 | 14.69 | 14.75 | 14.71 |
| 30                         | 14.69 | 14.75 | 14.75 | 14.76 | 14.75 | 14.74 | 14.75 | 14.75 | 14.73 | 14.74 | 14.72 | 14.73 | 14.70 | 14.69 | 14.75 | 14.72 |
| 20                         | 14.66 | 14.68 | 14.73 | 14.75 | 14.74 | 14.76 | 14.76 | 14.76 | 14.75 | 14.74 | 14.73 | 14.73 | 14.68 | 14.68 | 14.70 | 14.67 |
| 10                         | 14.64 | 14.68 | 14.72 | 14.70 | 14.74 | 14.73 | 14.74 | 14.75 | 14.74 | 14.72 | 14.72 | 14.72 | 14.61 | 14.65 | 14.64 | 14.61 |
| 5                          | 14.56 | 14.66 | 14.70 | 14.69 | 14.71 | 14.72 | 14.73 | 14.74 | 14.73 | 14.72 | 14.71 | 14.72 | 14.58 | 14.59 | 14.56 | 14.58 |
| 2                          | 14.58 | 14.67 | 14.71 | 14.71 | 14.72 | 14.73 | 14.73 | 14.76 | 14.72 | 14.70 | 14.70 | 14.70 |       |       |       |       |

Table 69: Test Data Fuel Mass (Kg/h)

| Fuel Mass kg/h | RPM |      |      |      |      |       |       |       |       |       |       |       |       |       |       |       |
|----------------|-----|------|------|------|------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
|                | 800 | 1000 | 1250 | 1500 | 1750 | 2000  | 2250  | 2500  | 3000  | 3500  | 4000  | 4500  | 5000  | 5500  | 6000  | 6500  |
| FL             |     | 3.24 | 5.22 | 7.52 | 9.39 | 11.35 | 12.92 | 14.34 | 18.08 | 18.92 | 21.54 | 22.34 | 25.55 | 26.61 | 27.62 | 25.11 |
| 200            |     |      |      |      |      | 11.34 | 12.96 | 14.25 | 17.78 | 19.47 |       |       |       |       |       |       |
| 190            |     |      |      |      |      | 10.77 | 12.04 | 13.39 | 16.91 | 18.46 |       |       |       |       |       |       |
| 180            |     |      |      |      |      | 9.11  | 10.05 | 11.26 | 12.52 | 15.24 | 17.76 | 20.61 |       |       |       |       |
| 170            |     |      |      |      | 7.51 | 8.77  | 9.38  | 10.52 | 11.72 | 14.06 | 17.14 | 18.91 | 21.41 |       |       |       |
| 160            |     |      |      |      | 7.10 | 8.08  | 8.74  | 9.77  | 10.88 | 13.05 | 15.06 | 17.46 | 19.80 | 23.68 |       |       |
| 150            |     |      |      |      | 6.52 | 7.46  | 8.17  | 9.12  | 10.19 | 11.98 | 14.00 | 16.18 | 18.15 | 20.99 | 24.47 |       |
| 140            |     |      |      | 5.19 | 6.04 | 6.84  | 7.63  | 8.45  | 9.44  | 11.01 | 12.93 | 14.87 | 16.65 | 18.92 | 21.63 | 25.58 |
| 130            |     |      |      | 4.73 | 5.46 | 6.16  | 6.96  | 7.73  | 8.55  | 10.05 | 11.89 | 13.84 | 15.40 | 17.30 | 19.71 | 22.93 |
| 120            |     |      |      | 4.35 | 4.93 | 5.75  | 6.39  | 7.07  | 7.79  | 9.15  | 10.95 | 12.86 | 14.24 | 15.88 | 18.00 | 20.45 |
| 110            |     |      |      | 3.22 | 3.91 | 4.52  | 5.24  | 5.78  | 6.43  | 7.13  | 8.42  | 9.97  | 11.65 | 13.06 | 14.58 | 16.31 |
| 100            |     |      |      | 2.97 | 3.43 | 4.13  | 4.66  | 5.20  | 5.78  | 6.48  | 7.71  | 9.03  | 10.53 | 11.88 | 13.38 | 15.00 |
| 90             |     |      |      | 2.56 | 3.00 | 3.60  | 4.11  | 4.55  | 5.13  | 5.77  | 6.90  | 8.05  | 9.36  | 10.70 | 12.11 | 13.59 |
| 80             |     |      |      | 2.20 | 2.66 | 3.15  | 3.59  | 4.05  | 4.55  | 5.13  | 6.11  | 7.13  | 8.39  | 9.56  | 10.95 | 12.32 |
| 70             |     |      |      | 1.89 | 2.33 | 2.77  | 3.21  | 3.60  | 4.07  | 4.56  | 5.40  | 6.32  | 7.45  | 8.44  | 9.71  | 10.92 |
| 60             |     |      |      | 1.63 | 2.02 | 2.42  | 2.78  | 3.12  | 3.54  | 4.02  | 4.75  | 5.54  | 6.50  | 7.39  | 8.51  | 9.60  |
| 50             |     |      |      | 1.38 | 1.73 | 2.08  | 2.38  | 2.70  | 3.03  | 3.41  | 4.09  | 4.80  | 5.60  | 6.41  | 7.31  | 8.25  |
| 40             |     |      |      | 1.04 | 1.16 | 1.46  | 1.76  | 2.01  | 2.28  | 2.57  | 2.87  | 3.46  | 4.10  | 4.77  | 5.48  | 6.27  |
| 30             |     |      |      | 0.89 | 0.95 | 1.19  | 1.42  | 1.67  | 1.88  | 2.13  | 2.36  | 2.85  | 3.41  | 3.94  | 4.55  | 5.21  |
| 20             |     |      |      | 0.61 | 0.73 | 0.93  | 1.10  | 1.30  | 1.48  | 1.65  | 1.84  | 2.21  | 2.67  | 3.13  | 3.64  | 4.18  |
| 10             |     |      |      | 0.44 | 0.51 | 0.65  | 0.78  | 0.93  | 1.05  | 1.16  | 1.29  | 1.63  | 1.92  | 2.38  | 2.72  | 3.18  |
| 5              |     |      |      | 0.36 | 0.42 | 0.53  | 0.63  | 0.79  | 0.88  | 0.98  | 1.09  | 1.32  | 1.60  | 1.99  | 2.33  | 2.73  |
| 2              |     |      |      | 0.32 | 0.39 | 0.46  | 0.56  | 0.66  | 0.78  | 0.86  | 0.98  | 1.22  | 1.44  | 1.83  | 2.09  |       |

Table 70: Test Data Specific Fuel Consumption (g/kWh)

| SFC g/kWh | RPM |       |       |       |        |        |        |        |        |       |        |        |       |        |        |        |
|-----------|-----|-------|-------|-------|--------|--------|--------|--------|--------|-------|--------|--------|-------|--------|--------|--------|
|           | 800 | 1000  | 1250  | 1500  | 1750   | 2000   | 2250   | 2500   | 3000   | 3500  | 4000   | 4500   | 5000  | 5500   | 6000   | 6500   |
| FL        |     | 287.6 | 285.7 | 286.3 | 277.3  | 273.5  | 274    | 272.9  | 284.5  | 278.4 | 273.2  | 271.1  | 294.5 | 295.5  | 300    | 292.5  |
| 200       |     |       |       |       |        | 273.7  | 274.8  | 271.9  | 282.5  | 269.3 |        |        |       |        |        |        |
| 190       |     |       |       |       |        | 270.5  | 268.8  | 268.6  | 283.9  | 266.5 |        |        |       |        |        |        |
| 180       |     |       |       |       |        | 276.2  | 266.7  | 265.2  | 265.7  | 269.8 | 270.1  | 273.2  |       |        |        |        |
| 170       |     |       |       |       | 285.5  | 281.6  | 263.9  | 263    | 263    | 273.7 | 265.6  | 267.3  |       |        |        |        |
| 160       |     |       |       |       | 282.1  | 275.6  | 260.9  | 259.1  | 259.8  | 259.6 | 260.7  | 262.8  | 282.5 |        |        |        |
| 150       |     |       |       |       | 277.5  | 271.2  | 259.7  | 258    | 259.6  | 254.3 | 254.5  | 256.7  | 256.8 | 267.9  | 283.2  |        |
| 140       |     |       |       |       | 284.6  | 275.6  | 266.6  | 258.8  | 256.3  | 257.5 | 250.5  | 251.9  | 254.7 | 257.9  | 268.4  | 290.8  |
| 130       |     |       |       |       | 278.2  | 266.7  | 258.4  | 255.4  | 252.3  | 251.2 | 246    | 249.4  | 253.8 | 251.2  | 254.1  | 263.2  |
| 120       |     |       |       |       | 276.7  | 262.2  | 261.7  | 255.7  | 250.2  | 247.8 | 242.6  | 249    | 255.1 | 251.7  | 252.5  | 260.6  |
| 110       |     |       |       |       | 288.5  | 271.5  | 261    | 260.2  | 251    | 247.9 | 247.4  | 243.5  | 247.4 | 254    | 251.9  | 252.9  |
| 100       |     |       |       |       | 287.4  | 261.8  | 263    | 254.1  | 246.9  | 245   | 247.3  | 245.5  | 246.5 | 250.1  | 251.8  | 255.1  |
| 90        |     |       |       |       | 273.2  | 254.6  | 255    | 249.1  | 242.7  | 242.1 | 245.1  | 244.3  | 243.9 | 249.3  | 252.3  | 256.4  |
| 80        |     |       |       |       | 263.4  | 253.8  | 249.6  | 245.2  | 241.1  | 241.1 | 244.7  | 243.2  | 243.2 | 250.4  | 253.7  | 261.5  |
| 70        |     |       |       |       | 259.2  | 253    | 252.7  | 250.4  | 246    | 246.4 | 248.6  | 245.4  | 246.3 | 252.8  | 255.9  | 265.1  |
| 60        |     |       |       |       | 259.8  | 256.6  | 255.6  | 252.6  | 249.4  | 250.6 | 255.8  | 251.8  | 251.8 | 259.2  | 261.1  | 271    |
| 50        |     |       |       |       | 265    | 264    | 265.7  | 260.2  | 257.6  | 257.3 | 260.4  | 260    | 262   | 268.1  | 271.8  | 279.2  |
| 40        |     |       |       |       | 300.4  | 282.6  | 278.3  | 278    | 274.2  | 271.7 | 273.2  | 273.8  | 275.8 | 279.8  | 284.1  | 290.9  |
| 30        |     |       |       |       | 314.7  | 310.6  | 305    | 305.3  | 303    | 300.9 | 300.5  | 300.5  | 302.1 | 308.9  | 313.8  | 321.5  |
| 20        |     |       |       |       | 362.4  | 370    | 356    | 364.4  | 355    | 355.5 | 350.8  | 353.8  | 352   | 363.7  | 373.7  | 386.5  |
| 10        |     |       |       |       | 489.7  | 558.9  | 519.8  | 515.4  | 509.1  | 515.7 | 509.8  | 512.1  | 493.5 | 525.8  | 570.2  | 599.7  |
| 5         |     |       |       |       | 763.3  | 956.7  | 858.1  | 868.2  | 730.5  | 826.4 | 880.8  | 843.4  | 963.8 | 882.6  | 958    | 997.8  |
| 2         |     |       |       |       | 1805.3 | 1462.4 | 3652.6 | 1772.2 | 1990.7 | 1617  | 1794.6 | 1179.4 | 1766  | 1988.3 | 2175.9 | 2188.9 |

Table 71: Test Data Turbo Out Temperature (Degrees)

| Turbo Out Temperature (Degrees C) | RPM |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |
|-----------------------------------|-----|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
|                                   | 800 | 1000  | 1250  | 1500  | 1750  | 2000  | 2250  | 2500  | 3000  | 3500  | 4000  | 4500  | 5000  | 5500  | 6000  | 6500  |
| FL                                |     | 574.0 | 643.5 | 700.8 | 780.0 | 853.6 | 879.2 | 917.4 | 928.8 | 949.6 | 975.3 | 967.7 | 995.1 | 995.5 | 980.7 | 946.0 |
| 200                               |     |       |       |       |       | 853.9 | 880.4 | 916.0 | 924.1 | 974.1 |       |       |       |       |       |       |
| 190                               |     |       |       |       |       | 839.3 | 863.0 | 898.9 | 909.2 | 953.1 |       |       |       |       |       |       |
| 180                               |     |       |       |       |       | 771.9 | 823.3 | 850.5 | 883.2 | 909.1 | 921.7 | 963.1 |       |       |       |       |
| 170                               |     |       |       |       | 700.1 | 729.1 | 808.3 | 836.8 | 865.7 | 901.4 | 879.5 | 944.7 | 953.6 |       |       |       |
| 160                               |     |       |       |       | 691.1 | 718.1 | 793.1 | 817.7 | 844.3 | 881.8 | 903.0 | 928.4 | 933.0 | 974.0 |       |       |
| 150                               |     |       |       |       | 678.9 | 709.9 | 771.7 | 795.2 | 819.8 | 855.8 | 882.8 | 907.4 | 916.1 | 948.1 | 982.2 |       |
| 140                               |     |       |       |       | 647.1 | 673.0 | 699.3 | 748.6 | 771.5 | 794.2 | 832.2 | 861.6 | 884.9 | 901.8 | 926.6 | 942.2 |
| 130                               |     |       |       |       | 637.2 | 660.6 | 688.4 | 721.4 | 740.9 | 762.0 | 803.1 | 838.0 | 864.9 | 879.1 | 901.9 | 915.1 |
| 120                               |     |       |       |       | 635.0 | 652.3 | 668.1 | 704.6 | 720.9 | 735.6 | 775.4 | 820.0 | 850.8 | 863.3 | 872.0 | 898.3 |
| 110                               |     |       |       |       | 573.9 | 623.2 | 648.2 | 653.4 | 684.0 | 706.4 | 720.8 | 761.5 | 800.9 | 832.3 | 846.8 | 850.9 |
| 100                               |     |       |       |       | 545.2 | 609.2 | 623.5 | 645.0 | 672.2 | 694.4 | 710.1 | 746.5 | 784.9 | 806.5 | 829.3 | 840.5 |
| 90                                |     |       |       |       | 538.7 | 595.5 | 610.1 | 636.2 | 665.1 | 686.1 | 700.5 | 736.4 | 767.9 | 791.9 | 816.3 | 826.9 |
| 80                                |     |       |       |       | 517.8 | 574.8 | 599.8 | 627.6 | 645.4 | 671.5 | 690.9 | 728.8 | 754.5 | 785.0 | 803.3 | 818.1 |
| 70                                |     |       |       |       | 499.7 | 555.6 | 588.2 | 613.4 | 629.6 | 656.9 | 675.9 | 707.5 | 738.7 | 771.1 | 790.7 | 810.7 |
| 60                                |     |       |       |       | 478.4 | 530.5 | 562.4 | 584.7 | 607.1 | 633.9 | 660.1 | 695.4 | 723.2 | 757.6 | 777.3 | 799.5 |
| 50                                |     |       |       |       | 459.7 | 505.5 | 538.9 | 559.2 | 580.7 | 604.9 | 630.6 | 674.6 | 708.4 | 741.9 | 763.0 | 787.2 |
| 40                                |     |       |       |       | 405.2 | 442.6 | 482.5 | 512.6 | 530.7 | 549.3 | 582.2 | 605.6 | 656.9 | 692.9 | 723.2 | 748.6 |
| 30                                |     |       |       |       | 384.4 | 415.8 | 458.8 | 490.8 | 512.9 | 529.6 | 563.4 | 588.3 | 634.9 | 673.2 | 705.8 | 735.0 |
| 20                                |     |       |       |       | 333.6 | 379.5 | 425.6 | 473.1 | 500.8 | 525.0 | 548.1 | 573.2 | 615.8 | 656.2 | 691.7 | 728.8 |
| 10                                |     |       |       |       | 316.8 | 359.1 | 428.3 | 452.8 | 482.0 | 497.9 | 519.2 | 536.1 | 594.2 | 636.7 | 683.4 | 713.2 |
| 5                                 |     |       |       |       | 250.8 | 312.8 | 403.7 | 446.3 | 491.2 | 540.0 | 553.2 | 563.9 | 618.3 | 645.3 | 680.9 | 700.3 |
| 2                                 |     |       |       |       | 239.4 | 303.6 | 389.7 | 398.8 | 453.0 | 533.9 | 529.2 | 562.3 | 639.8 | 671.1 | 681.2 | 697.7 |

Table 72: Test Data Intercooler Air Out (Degrees)

| Intercooler Air Out (Degrees C) | RPM  |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |
|---------------------------------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|
|                                 | 800  | 1000 | 1250 | 1500 | 1750 | 2000 | 2250 | 2500 | 3000 | 3500 | 4000 | 4500 | 5000 | 5500 | 6000 | 6500 |
| FL                              |      | 25   | 39.8 | 40.1 | 40.1 | 40   | 40.3 | 40   | 40.1 | 40.1 | 40.4 | 40.2 | 50.4 | 50.4 | 50.2 | 50.2 |
| 200                             |      |      |      |      |      | 40.1 | 40.1 | 40.1 | 40.2 | 40.2 | 40.4 |      |      |      |      |      |
| 190                             |      |      |      |      |      | 40.1 | 40.1 | 40.2 | 40.1 | 40.2 |      |      |      |      |      |      |
| 180                             |      |      |      |      | 40.1 | 40.2 | 40.1 | 40.1 | 40.2 | 40.1 | 40.3 |      |      |      |      |      |
| 170                             |      |      |      | 40.1 | 40.2 | 40   | 40.1 | 40   | 40.1 | 40.2 | 40.1 | 40.2 |      |      |      |      |
| 160                             |      |      |      | 40.3 | 40.2 | 40.3 | 40.3 | 40.2 | 40.2 | 40.2 | 40.3 | 40.3 | 50.1 |      |      |      |
| 150                             |      |      |      | 40.7 | 40.4 | 40.5 | 40.4 | 40.2 | 40.5 | 40.2 | 40.2 | 40.3 | 45.1 | 50.2 |      |      |
| 140                             |      |      | 40.1 | 41   | 41.3 | 41.4 | 40.5 | 41.2 | 40.7 | 40.2 | 39.9 | 40.1 | 40.3 | 40.3 | 50.3 |      |
| 130                             |      |      | 34.4 | 34.9 | 35.2 | 35.4 | 35.4 | 35.7 | 35.6 | 35.5 | 35.4 | 35.3 | 40.1 | 40.2 | 50.4 |      |
| 120                             |      |      | 30.1 | 30   | 30.1 | 30   | 30   | 30.1 | 30.1 | 30.1 | 30.2 | 30.1 | 35.3 | 40.2 | 40.4 | 50   |
| 110                             |      | 25.1 | 30   | 30.1 | 30   | 30.1 | 30   | 30   | 30   | 30   | 30.1 | 30.1 | 30.2 | 35.2 | 40.1 | 40.2 |
| 100                             |      | 25   | 30   | 30   | 30.1 | 30.1 | 30   | 30   | 30   | 30   | 30.1 | 30.1 | 30.1 | 30.2 | 35.1 | 40   |
| 90                              |      | 25   | 29.5 | 29.6 | 29.5 | 29.5 | 29.5 | 29.5 | 29.5 | 29.5 | 29.5 | 29.5 | 29.5 | 29.5 | 34.6 | 39   |
| 80                              |      | 25   | 29   | 29.1 | 29.1 | 29.1 | 29.1 | 29   | 29.1 | 29   | 29   | 29   | 29   | 29   | 34   | 38   |
| 70                              |      | 25   | 28.4 | 28.6 | 28.5 | 28.5 | 28.5 | 28.5 | 28.5 | 28.5 | 28.6 | 28.5 | 28.5 | 28.5 | 33.6 | 37.1 |
| 60                              |      | 25   | 28   | 28.1 | 28.1 | 28   | 28.1 | 28   | 28   | 28.1 | 28   | 28   | 28   | 28   | 33   | 36.2 |
| 50                              |      | 25   | 27.5 | 27.6 | 27.6 | 27.6 | 27.5 | 27.6 | 27.5 | 27.6 | 27.5 | 27.5 | 27.5 | 27.5 | 32.6 | 35.2 |
| 40                              | 25   | 25   | 27   | 27.1 | 27   | 27.1 | 27   | 27   | 27   | 27   | 27.1 | 27   | 27   | 27   | 32.2 | 34.2 |
| 30                              | 25   | 25   | 26.5 | 26.6 | 26.5 | 26.5 | 26.5 | 26.5 | 26.5 | 26.5 | 26.5 | 26.5 | 26.5 | 26.5 | 32.2 | 33.2 |
| 20                              | 24.9 | 25   | 26   | 26   | 26   | 26   | 26   | 26   | 26   | 26   | 26   | 26   | 26   | 26   | 33.1 | 32   |
| 10                              | 24.1 | 25   | 25.5 | 25.4 | 25.4 | 25.4 | 25.4 | 25.3 | 25.4 | 25.4 | 25.5 | 25.5 | 25.5 | 25.4 | 31.1 | 30.8 |
| 5                               | 23.8 | 25   | 25.3 | 24.7 | 24.9 | 24.7 | 24.9 | 24.5 | 24.6 | 25   | 25.1 | 25.2 | 25.2 | 25.6 | 28.8 | 29.4 |
| 2                               | 25.2 | 25.1 | 25.2 | 23.9 | 23.9 | 24.1 | 23.9 | 24.2 | 24.2 | 24   | 24.6 | 24.9 |      |      |      |      |

Table 73: Test Data BMEP (kN/m<sup>2</sup>)

| BMEP kN/m <sup>2</sup> | RPM |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |
|------------------------|-----|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|
|                        | 800 | 1000 | 1250 | 1500 | 1750 | 2000 | 2250 | 2500 | 3000 | 3500 | 4000 | 4500 | 5000 | 5500 | 6000 | 6500 |
| FL                     |     | 1355 | 1757 | 2104 | 2324 | 2493 | 2517 | 2523 | 2546 | 2513 | 2368 | 2200 | 2085 | 1966 | 1843 | 1587 |
| 200                    |     |      |      |      |      | 2489 | 2517 | 2518 | 2520 | 2482 |      |      |      |      |      |      |
| 190                    |     |      |      |      |      | 2392 | 2391 | 2394 | 2387 | 2379 |      |      |      |      |      |      |
| 180                    |     |      |      |      | 2266 | 2263 | 2266 | 2266 | 2261 | 2257 | 2267 |      |      |      |      |      |
| 170                    |     |      |      | 2108 | 2137 | 2136 | 2138 | 2141 | 2140 | 2149 | 2138 | 2138 |      |      |      |      |
| 160                    |     |      |      | 2015 | 2012 | 2013 | 2014 | 2012 | 2013 | 2014 | 2012 | 2010 | 2014 |      |      |      |
| 150                    |     |      |      | 1883 | 1887 | 1891 | 1887 | 1887 | 1886 | 1887 | 1893 | 1886 | 1888 | 1888 |      |      |
| 140                    |     |      | 1754 | 1756 | 1761 | 1771 | 1759 | 1761 | 1759 | 1762 | 1752 | 1762 | 1762 | 1760 | 1761 |      |
| 130                    |     |      | 1634 | 1638 | 1635 | 1636 | 1636 | 1635 | 1635 | 1636 | 1638 | 1636 | 1636 | 1635 | 1637 |      |
| 120                    |     |      | 1510 | 1505 | 1510 | 1502 | 1509 | 1510 | 1511 | 1509 | 1514 | 1510 | 1510 | 1509 | 1510 | 1510 |
| 110                    |     | 1346 | 1384 | 1386 | 1383 | 1384 | 1384 | 1384 | 1385 | 1384 | 1377 | 1384 | 1385 | 1384 | 1385 | 1384 |
| 100                    |     | 1243 | 1258 | 1258 | 1258 | 1266 | 1258 | 1259 | 1258 | 1258 | 1264 | 1259 | 1260 | 1259 | 1260 | 1259 |
| 90                     |     | 1128 | 1133 | 1129 | 1132 | 1125 | 1132 | 1132 | 1131 | 1133 | 1128 | 1132 | 1135 | 1132 | 1132 | 1132 |
| 80                     |     | 1004 | 1007 | 1009 | 1006 | 1009 | 1007 | 1007 | 1006 | 1006 | 1006 | 1006 | 1006 | 1006 | 1006 | 1006 |
| 70                     |     | 878  | 884  | 877  | 880  | 878  | 881  | 881  | 881  | 881  | 885  | 881  | 880  | 880  | 880  | 881  |
| 60                     |     | 754  | 755  | 758  | 754  | 750  | 754  | 755  | 755  | 755  | 753  | 755  | 755  | 755  | 755  | 755  |
| 50                     |     | 627  | 629  | 628  | 629  | 630  | 629  | 629  | 630  | 629  | 627  | 629  | 629  | 629  | 629  | 628  |
| 40                     | 473 | 494  | 503  | 506  | 502  | 503  | 503  | 503  | 502  | 503  | 504  | 503  | 503  | 505  | 503  | 502  |
| 30                     | 393 | 368  | 376  | 374  | 377  | 375  | 378  | 377  | 377  | 379  | 377  | 377  | 377  | 378  | 378  | 378  |
| 20                     | 251 | 236  | 250  | 242  | 251  | 251  | 251  | 250  | 252  | 252  | 252  | 251  | 251  | 252  | 253  | 251  |
| 10                     | 135 | 109  | 120  | 121  | 126  | 122  | 122  | 121  | 132  | 125  | 125  | 121  | 125  | 130  | 134  | 135  |
| 5                      | 71  | 52   | 59   | 58   | 74   | 64   | 60   | 62   | 55   | 62   | 63   | 62   | 61   | 71   | 66   | 69   |
| 2                      | 26  | 32   | 12   | 25   | 23   | 29   | 26   | 26   | 28   | 25   | 25   | 26   |      |      |      |      |

## 6.7 Example of Ideal Otto Cycle Calculations

| 1000RPM                           |             |           |          |        |         |           |         |         |
|-----------------------------------|-------------|-----------|----------|--------|---------|-----------|---------|---------|
| Standard Cycle - Using Polynomial |             |           |          |        |         |           |         |         |
| Average Cylinder Pressure         | Temperature | Cp        |          |        |         | Cv        | CV      | γ       |
|                                   |             | IsoOctane | Nitrogen | Oxygen | Mixture | Mixture   | Mixture |         |
| Pascals                           | Kelvin      | KJ/Kmol.K |          |        |         | KJ/Kmol.K | J/Kg.K  |         |
| 132100                            | 298         | 188.60    | 28.98    | 29.35  | 31.43   | 23.12     | 767.58  | 1.35962 |
| 132070.92                         | 297.98      | 188.59    | 28.98    | 29.35  | 31.43   | 23.12     | 767.57  | 1.35962 |
| 132061.22                         | 297.98      | 188.59    | 28.98    | 29.35  | 31.43   | 23.12     | 767.57  | 1.35962 |
| 132070.92                         | 297.98      | 188.59    | 28.98    | 29.35  | 31.43   | 23.12     | 767.57  | 1.35962 |
| 132095.15                         | 298.00      | 188.60    | 28.98    | 29.35  | 31.43   | 23.12     | 767.57  | 1.35962 |
| 132133.94                         | 298.02      | 188.61    | 28.98    | 29.35  | 31.43   | 23.12     | 767.58  | 1.35962 |
| 132197.03                         | 298.06      | 188.63    | 28.98    | 29.35  | 31.44   | 23.12     | 767.60  | 1.35961 |
| 132269.87                         | 298.10      | 188.66    | 28.98    | 29.35  | 31.44   | 23.12     | 767.62  | 1.35960 |
| 132367.12                         | 298.16      | 188.69    | 28.98    | 29.35  | 31.44   | 23.12     | 767.64  | 1.35959 |
| 132479.09                         | 298.23      | 188.73    | 28.98    | 29.36  | 31.44   | 23.12     | 767.67  | 1.35957 |
| 132610.76                         | 298.30      | 188.77    | 28.98    | 29.36  | 31.44   | 23.12     | 767.70  | 1.35956 |
| 132757.31                         | 298.39      | 188.82    | 28.98    | 29.36  | 31.44   | 23.13     | 767.74  | 1.35954 |

|           |        |        |       |       |       |       |        |         |
|-----------|--------|--------|-------|-------|-------|-------|--------|---------|
| 132923.75 | 298.49 | 188.87 | 28.98 | 29.36 | 31.44 | 23.13 | 767.78 | 1.35952 |
| 133105.28 | 298.60 | 188.93 | 28.98 | 29.36 | 31.44 | 23.13 | 767.83 | 1.35950 |
| 133306.94 | 298.72 | 189.00 | 28.98 | 29.36 | 31.44 | 23.13 | 767.88 | 1.35948 |
| 133528.87 | 298.85 | 189.07 | 28.98 | 29.36 | 31.45 | 23.13 | 767.93 | 1.35945 |
| 133766.31 | 298.99 | 189.15 | 28.98 | 29.36 | 31.45 | 23.13 | 767.99 | 1.35942 |
| 134024.35 | 299.14 | 189.23 | 28.99 | 29.37 | 31.45 | 23.13 | 768.06 | 1.35939 |
| 134303.21 | 299.31 | 189.32 | 28.99 | 29.37 | 31.45 | 23.14 | 768.13 | 1.35936 |
| 134598.08 | 299.48 | 189.41 | 28.99 | 29.37 | 31.45 | 23.14 | 768.20 | 1.35933 |
| 134914.19 | 299.67 | 189.52 | 28.99 | 29.37 | 31.46 | 23.14 | 768.28 | 1.35929 |
| 135251.77 | 299.86 | 189.62 | 28.99 | 29.37 | 31.46 | 23.14 | 768.36 | 1.35925 |
| 135606.03 | 300.07 | 189.74 | 28.99 | 29.38 | 31.46 | 23.15 | 768.45 | 1.35921 |
| 135982.27 | 300.29 | 189.86 | 28.99 | 29.38 | 31.46 | 23.15 | 768.55 | 1.35916 |
| 136380.80 | 300.52 | 189.98 | 28.99 | 29.38 | 31.47 | 23.15 | 768.64 | 1.35912 |
| 136796.80 | 300.77 | 190.12 | 28.99 | 29.38 | 31.47 | 23.16 | 768.75 | 1.35907 |
| 137235.70 | 301.02 | 190.26 | 28.99 | 29.39 | 31.47 | 23.16 | 768.85 | 1.35902 |
| 137697.86 | 301.29 | 190.40 | 28.99 | 29.39 | 31.48 | 23.16 | 768.97 | 1.35897 |
| 138178.43 | 301.56 | 190.55 | 28.99 | 29.39 | 31.48 | 23.17 | 769.09 | 1.35891 |
| 138682.99 | 301.86 | 190.71 | 28.99 | 29.40 | 31.48 | 23.17 | 769.21 | 1.35886 |
| 139211.95 | 302.16 | 190.88 | 28.99 | 29.40 | 31.49 | 23.17 | 769.34 | 1.35880 |
| 139765.78 | 302.48 | 191.05 | 29.00 | 29.40 | 31.49 | 23.18 | 769.47 | 1.35873 |
| 140339.56 | 302.80 | 191.23 | 29.00 | 29.41 | 31.50 | 23.18 | 769.61 | 1.35867 |
| 140939.10 | 303.14 | 191.41 | 29.00 | 29.41 | 31.50 | 23.19 | 769.75 | 1.35860 |
| 141564.91 | 303.50 | 191.61 | 29.00 | 29.41 | 31.50 | 23.19 | 769.90 | 1.35853 |
| 142212.05 | 303.86 | 191.81 | 29.00 | 29.42 | 31.51 | 23.20 | 770.06 | 1.35846 |
| 142886.51 | 304.24 | 192.01 | 29.00 | 29.42 | 31.51 | 23.20 | 770.22 | 1.35838 |
| 143588.90 | 304.64 | 192.23 | 29.00 | 29.43 | 31.52 | 23.20 | 770.39 | 1.35831 |
| 144319.85 | 305.05 | 192.45 | 29.00 | 29.43 | 31.52 | 23.21 | 770.56 | 1.35823 |
| 145074.33 | 305.47 | 192.68 | 29.00 | 29.44 | 31.53 | 23.22 | 770.74 | 1.35814 |
| 145858.64 | 305.90 | 192.91 | 29.01 | 29.44 | 31.54 | 23.22 | 770.92 | 1.35806 |
| 146673.52 | 306.35 | 193.16 | 29.01 | 29.45 | 31.54 | 23.23 | 771.11 | 1.35797 |
| 147519.75 | 306.81 | 193.41 | 29.01 | 29.45 | 31.55 | 23.23 | 771.31 | 1.35788 |
| 148392.20 | 307.29 | 193.67 | 29.01 | 29.46 | 31.55 | 23.24 | 771.51 | 1.35779 |
| 149297.54 | 307.79 | 193.93 | 29.01 | 29.46 | 31.56 | 23.24 | 771.72 | 1.35769 |
| 150236.66 | 308.29 | 194.21 | 29.01 | 29.47 | 31.57 | 23.25 | 771.93 | 1.35759 |
| 151210.49 | 308.82 | 194.49 | 29.01 | 29.47 | 31.57 | 23.26 | 772.15 | 1.35749 |
| 152213.83 | 309.36 | 194.78 | 29.02 | 29.48 | 31.58 | 23.26 | 772.38 | 1.35738 |
| 153253.77 | 309.91 | 195.08 | 29.02 | 29.49 | 31.59 | 23.27 | 772.62 | 1.35727 |
| 154331.38 | 310.48 | 195.39 | 29.02 | 29.49 | 31.59 | 23.28 | 772.86 | 1.35716 |
| 155441.38 | 311.07 | 195.71 | 29.02 | 29.50 | 31.60 | 23.29 | 773.11 | 1.35705 |
| 156591.23 | 311.67 | 196.03 | 29.02 | 29.50 | 31.61 | 23.29 | 773.36 | 1.35693 |
| 157782.18 | 312.30 | 196.37 | 29.03 | 29.51 | 31.62 | 23.30 | 773.62 | 1.35681 |
| 159008.86 | 312.93 | 196.71 | 29.03 | 29.52 | 31.62 | 23.31 | 773.89 | 1.35668 |
| 160279.16 | 313.59 | 197.06 | 29.03 | 29.53 | 31.63 | 23.32 | 774.17 | 1.35656 |
| 161587.66 | 314.26 | 197.42 | 29.03 | 29.53 | 31.64 | 23.33 | 774.45 | 1.35643 |
| 162942.55 | 314.95 | 197.79 | 29.03 | 29.54 | 31.65 | 23.34 | 774.74 | 1.35629 |
| 164345.42 | 315.66 | 198.17 | 29.04 | 29.55 | 31.66 | 23.35 | 775.04 | 1.35615 |
| 165790.79 | 316.39 | 198.56 | 29.04 | 29.56 | 31.67 | 23.35 | 775.35 | 1.35601 |
| 167287.37 | 317.13 | 198.96 | 29.04 | 29.56 | 31.68 | 23.36 | 775.66 | 1.35587 |
| 168837.03 | 317.90 | 199.37 | 29.04 | 29.57 | 31.69 | 23.37 | 775.99 | 1.35572 |
| 170426.68 | 318.68 | 199.79 | 29.05 | 29.58 | 31.70 | 23.38 | 776.32 | 1.35557 |
| 172080.58 | 319.49 | 200.22 | 29.05 | 29.59 | 31.71 | 23.39 | 776.66 | 1.35541 |

|           |        |        |       |       |       |       |        |         |
|-----------|--------|--------|-------|-------|-------|-------|--------|---------|
| 173777.93 | 320.32 | 200.66 | 29.05 | 29.60 | 31.72 | 23.40 | 777.00 | 1.35526 |
| 175536.06 | 321.16 | 201.11 | 29.05 | 29.61 | 31.73 | 23.41 | 777.36 | 1.35509 |
| 177357.36 | 322.03 | 201.57 | 29.06 | 29.62 | 31.74 | 23.43 | 777.73 | 1.35493 |
| 179236.14 | 322.92 | 202.04 | 29.06 | 29.63 | 31.75 | 23.44 | 778.10 | 1.35475 |
| 181174.62 | 323.83 | 202.52 | 29.06 | 29.64 | 31.76 | 23.45 | 778.48 | 1.35458 |
| 183175.14 | 324.77 | 203.02 | 29.07 | 29.65 | 31.78 | 23.46 | 778.88 | 1.35440 |
| 185240.17 | 325.72 | 203.52 | 29.07 | 29.66 | 31.79 | 23.47 | 779.28 | 1.35422 |
| 187381.17 | 326.70 | 204.04 | 29.07 | 29.67 | 31.80 | 23.49 | 779.69 | 1.35403 |
| 189592.38 | 327.70 | 204.57 | 29.07 | 29.68 | 31.81 | 23.50 | 780.11 | 1.35384 |
| 191876.73 | 328.73 | 205.11 | 29.08 | 29.69 | 31.83 | 23.51 | 780.54 | 1.35364 |
| 194237.31 | 329.78 | 205.66 | 29.08 | 29.70 | 31.84 | 23.52 | 780.98 | 1.35344 |
| 196667.75 | 330.86 | 206.22 | 29.09 | 29.71 | 31.85 | 23.54 | 781.43 | 1.35324 |
| 199190.59 | 331.96 | 206.80 | 29.09 | 29.73 | 31.87 | 23.55 | 781.90 | 1.35303 |
| 201800.05 | 333.09 | 207.39 | 29.09 | 29.74 | 31.88 | 23.57 | 782.37 | 1.35282 |
| 204489.74 | 334.24 | 207.99 | 29.10 | 29.75 | 31.89 | 23.58 | 782.85 | 1.35260 |
| 207273.59 | 335.42 | 208.61 | 29.10 | 29.76 | 31.91 | 23.60 | 783.35 | 1.35238 |
| 210155.96 | 336.63 | 209.24 | 29.10 | 29.78 | 31.93 | 23.61 | 783.86 | 1.35215 |
| 213130.42 | 337.86 | 209.88 | 29.11 | 29.79 | 31.94 | 23.63 | 784.37 | 1.35192 |
| 216212.40 | 339.13 | 210.54 | 29.11 | 29.80 | 31.96 | 23.64 | 784.90 | 1.35168 |
| 219395.46 | 340.42 | 211.21 | 29.12 | 29.82 | 31.97 | 23.66 | 785.44 | 1.35144 |
| 222696.18 | 341.75 | 211.89 | 29.12 | 29.83 | 31.99 | 23.68 | 786.00 | 1.35119 |
| 226108.17 | 343.10 | 212.59 | 29.13 | 29.84 | 32.01 | 23.69 | 786.56 | 1.35094 |
| 229636.70 | 344.48 | 213.30 | 29.13 | 29.86 | 32.02 | 23.71 | 787.14 | 1.35068 |
| 233300.29 | 345.90 | 214.03 | 29.14 | 29.87 | 32.04 | 23.73 | 787.73 | 1.35042 |
| 237079.38 | 347.35 | 214.77 | 29.14 | 29.89 | 32.06 | 23.75 | 788.34 | 1.35015 |
| 240992.90 | 348.82 | 215.53 | 29.15 | 29.91 | 32.08 | 23.76 | 788.95 | 1.34987 |
| 245061.71 | 350.34 | 216.31 | 29.15 | 29.92 | 32.10 | 23.78 | 789.59 | 1.34959 |
| 249265.25 | 351.89 | 217.10 | 29.16 | 29.94 | 32.12 | 23.80 | 790.23 | 1.34931 |
| 253609.96 | 353.46 | 217.90 | 29.16 | 29.95 | 32.14 | 23.82 | 790.89 | 1.34902 |
| 258133.52 | 355.09 | 218.72 | 29.17 | 29.97 | 32.16 | 23.84 | 791.56 | 1.34872 |
| 262814.31 | 356.74 | 219.56 | 29.18 | 29.99 | 32.18 | 23.86 | 792.25 | 1.34842 |
| 267660.24 | 358.43 | 220.41 | 29.18 | 30.01 | 32.20 | 23.88 | 792.96 | 1.34811 |
| 272679.74 | 360.15 | 221.28 | 29.19 | 30.02 | 32.22 | 23.91 | 793.67 | 1.34779 |
| 277899.31 | 361.92 | 222.17 | 29.19 | 30.04 | 32.24 | 23.93 | 794.41 | 1.34747 |
| 283312.23 | 363.72 | 223.08 | 29.20 | 30.06 | 32.27 | 23.95 | 795.16 | 1.34715 |
| 288928.89 | 365.57 | 224.00 | 29.21 | 30.08 | 32.29 | 23.97 | 795.92 | 1.34681 |
| 294760.37 | 367.45 | 224.95 | 29.22 | 30.10 | 32.31 | 24.00 | 796.70 | 1.34647 |
| 300798.53 | 369.38 | 225.90 | 29.22 | 30.12 | 32.34 | 24.02 | 797.50 | 1.34612 |
| 307074.75 | 371.34 | 226.88 | 29.23 | 30.14 | 32.36 | 24.05 | 798.32 | 1.34577 |
| 313602.66 | 373.35 | 227.88 | 29.24 | 30.16 | 32.39 | 24.07 | 799.15 | 1.34541 |
| 320374.51 | 375.41 | 228.89 | 29.25 | 30.18 | 32.41 | 24.10 | 800.00 | 1.34504 |
| 327426.76 | 377.51 | 229.93 | 29.25 | 30.20 | 32.44 | 24.12 | 800.87 | 1.34467 |
| 334727.92 | 379.65 | 230.98 | 29.26 | 30.22 | 32.46 | 24.15 | 801.75 | 1.34429 |
| 342340.71 | 381.84 | 232.06 | 29.27 | 30.25 | 32.49 | 24.18 | 802.66 | 1.34390 |
| 350258.31 | 384.08 | 233.15 | 29.28 | 30.27 | 32.52 | 24.20 | 803.58 | 1.34351 |
| 358471.21 | 386.37 | 234.26 | 29.29 | 30.29 | 32.55 | 24.23 | 804.52 | 1.34310 |
| 367023.40 | 388.70 | 235.40 | 29.30 | 30.32 | 32.58 | 24.26 | 805.48 | 1.34269 |
| 375935.22 | 391.09 | 236.55 | 29.31 | 30.34 | 32.61 | 24.29 | 806.47 | 1.34228 |
| 385197.80 | 393.52 | 237.73 | 29.32 | 30.36 | 32.64 | 24.32 | 807.47 | 1.34185 |
| 394862.96 | 396.02 | 238.93 | 29.33 | 30.39 | 32.67 | 24.35 | 808.49 | 1.34142 |
| 404922.53 | 398.56 | 240.15 | 29.34 | 30.41 | 32.70 | 24.38 | 809.53 | 1.34098 |
| 415364.34 | 401.15 | 241.38 | 29.35 | 30.44 | 32.73 | 24.42 | 810.59 | 1.34053 |

|            |        |        |       |       |       |       |        |         |
|------------|--------|--------|-------|-------|-------|-------|--------|---------|
| 426281.73  | 403.80 | 242.65 | 29.36 | 30.47 | 32.76 | 24.45 | 811.68 | 1.34008 |
| 437667.76  | 406.51 | 243.93 | 29.37 | 30.49 | 32.80 | 24.48 | 812.79 | 1.33961 |
| 449510.90  | 409.27 | 245.24 | 29.38 | 30.52 | 32.83 | 24.52 | 813.92 | 1.33914 |
| 461878.64  | 412.09 | 246.57 | 29.39 | 30.55 | 32.87 | 24.55 | 815.07 | 1.33866 |
| 474759.94  | 414.97 | 247.92 | 29.41 | 30.58 | 32.90 | 24.59 | 816.24 | 1.33818 |
| 488184.25  | 417.91 | 249.29 | 29.42 | 30.61 | 32.94 | 24.62 | 817.44 | 1.33768 |
| 502232.02  | 420.91 | 250.68 | 29.43 | 30.63 | 32.97 | 24.66 | 818.66 | 1.33718 |
| 516893.43  | 423.98 | 252.10 | 29.44 | 30.66 | 33.01 | 24.70 | 819.91 | 1.33667 |
| 532151.67  | 427.09 | 253.54 | 29.46 | 30.69 | 33.05 | 24.73 | 821.17 | 1.33615 |
| 548151.90  | 430.29 | 255.01 | 29.47 | 30.72 | 33.09 | 24.77 | 822.47 | 1.33562 |
| 564826.24  | 433.54 | 256.50 | 29.49 | 30.76 | 33.13 | 24.81 | 823.78 | 1.33508 |
| 582211.75  | 436.85 | 258.01 | 29.50 | 30.79 | 33.17 | 24.85 | 825.12 | 1.33454 |
| 600414.59  | 440.24 | 259.54 | 29.52 | 30.82 | 33.21 | 24.89 | 826.49 | 1.33399 |
| 619417.96  | 443.68 | 261.10 | 29.53 | 30.85 | 33.25 | 24.94 | 827.88 | 1.33342 |
| 639267.99  | 447.20 | 262.67 | 29.55 | 30.89 | 33.29 | 24.98 | 829.29 | 1.33286 |
| 660014.12  | 450.78 | 264.28 | 29.56 | 30.92 | 33.34 | 25.02 | 830.73 | 1.33228 |
| 681792.38  | 454.44 | 265.91 | 29.58 | 30.95 | 33.38 | 25.07 | 832.20 | 1.33169 |
| 704410.87  | 458.15 | 267.55 | 29.60 | 30.99 | 33.43 | 25.11 | 833.69 | 1.33110 |
| 728179.80  | 461.95 | 269.22 | 29.61 | 31.02 | 33.47 | 25.16 | 835.21 | 1.33050 |
| 752983.56  | 465.81 | 270.91 | 29.63 | 31.06 | 33.52 | 25.20 | 836.75 | 1.32989 |
| 778875.27  | 469.73 | 272.62 | 29.65 | 31.09 | 33.57 | 25.25 | 838.31 | 1.32927 |
| 806022.03  | 473.74 | 274.35 | 29.67 | 31.13 | 33.61 | 25.30 | 839.90 | 1.32865 |
| 834385.79  | 477.81 | 276.11 | 29.69 | 31.17 | 33.66 | 25.35 | 841.52 | 1.32802 |
| 864030.53  | 481.94 | 277.88 | 29.71 | 31.21 | 33.71 | 25.40 | 843.16 | 1.32738 |
| 895023.86  | 486.15 | 279.67 | 29.73 | 31.24 | 33.76 | 25.45 | 844.82 | 1.32674 |
| 927295.52  | 490.41 | 281.48 | 29.75 | 31.28 | 33.81 | 25.50 | 846.51 | 1.32609 |
| 961044.35  | 494.74 | 283.30 | 29.77 | 31.32 | 33.86 | 25.55 | 848.21 | 1.32543 |
| 996347.91  | 499.14 | 285.14 | 29.79 | 31.36 | 33.92 | 25.60 | 849.94 | 1.32477 |
| 1033287.93 | 503.62 | 287.01 | 29.81 | 31.40 | 33.97 | 25.65 | 851.70 | 1.32410 |
| 1071585.92 | 508.12 | 288.87 | 29.83 | 31.44 | 34.02 | 25.71 | 853.46 | 1.32343 |
| 1111648.63 | 512.70 | 290.75 | 29.86 | 31.48 | 34.08 | 25.76 | 855.25 | 1.32275 |
| 1153565.76 | 517.35 | 292.65 | 29.88 | 31.52 | 34.13 | 25.82 | 857.06 | 1.32207 |
| 1196989.17 | 522.03 | 294.55 | 29.90 | 31.56 | 34.18 | 25.87 | 858.88 | 1.32139 |
| 1242163.77 | 526.76 | 296.45 | 29.93 | 31.60 | 34.24 | 25.93 | 860.71 | 1.32070 |
| 1289137.68 | 531.53 | 298.36 | 29.95 | 31.64 | 34.30 | 25.98 | 862.56 | 1.32002 |
| 1337955.75 | 536.34 | 300.27 | 29.98 | 31.68 | 34.35 | 26.04 | 864.42 | 1.31933 |
| 1388658.57 | 541.19 | 302.19 | 30.00 | 31.72 | 34.41 | 26.09 | 866.28 | 1.31864 |
| 1440976.08 | 546.05 | 304.10 | 30.02 | 31.76 | 34.46 | 26.15 | 868.15 | 1.31796 |
| 1495201.79 | 550.93 | 306.00 | 30.05 | 31.80 | 34.52 | 26.21 | 870.02 | 1.31727 |
| 1551005.65 | 555.82 | 307.89 | 30.08 | 31.84 | 34.58 | 26.26 | 871.89 | 1.31660 |
| 1608696.79 | 560.72 | 309.78 | 30.10 | 31.88 | 34.63 | 26.32 | 873.75 | 1.31592 |
| 1667479.48 | 565.57 | 311.63 | 30.13 | 31.92 | 34.69 | 26.37 | 875.60 | 1.31525 |
| 1728438.87 | 570.46 | 313.48 | 30.15 | 31.96 | 34.74 | 26.43 | 877.45 | 1.31459 |
| 1790273.05 | 575.28 | 315.30 | 30.18 | 32.00 | 34.80 | 26.48 | 879.27 | 1.31394 |
| 1853231.43 | 580.05 | 317.08 | 30.20 | 32.04 | 34.85 | 26.54 | 881.07 | 1.31330 |
| 1917645.52 | 584.80 | 318.84 | 30.23 | 32.08 | 34.91 | 26.59 | 882.85 | 1.31266 |
| 1982340.34 | 589.44 | 320.56 | 30.25 | 32.12 | 34.96 | 26.64 | 884.59 | 1.31205 |
| 2047560.71 | 593.99 | 322.23 | 30.28 | 32.15 | 35.01 | 26.70 | 886.29 | 1.31145 |
| 2113643.14 | 598.49 | 323.86 | 30.30 | 32.19 | 35.06 | 26.75 | 887.97 | 1.31086 |
| 2178509.50 | 602.80 | 325.42 | 30.32 | 32.22 | 35.11 | 26.79 | 889.57 | 1.31030 |
| 2243626.93 | 607.01 | 326.94 | 30.35 | 32.25 | 35.16 | 26.84 | 891.13 | 1.30976 |
| 2308049.12 | 611.09 | 328.40 | 30.37 | 32.28 | 35.20 | 26.89 | 892.64 | 1.30923 |

|             |         |         |       |       |       |       |         |         |
|-------------|---------|---------|-------|-------|-------|-------|---------|---------|
| 2370669.25  | 614.97  | 329.78  | 30.39 | 32.31 | 35.24 | 26.93 | 894.07  | 1.30874 |
| 2430984.71  | 618.62  | 331.07  | 30.41 | 32.34 | 35.29 | 26.97 | 895.41  | 1.30828 |
| 2490062.82  | 622.13  | 332.31  | 30.43 | 32.37 | 35.32 | 27.01 | 896.70  | 1.30783 |
| 2545911.52  | 625.39  | 333.45  | 30.45 | 32.39 | 35.36 | 27.05 | 897.90  | 1.30742 |
| 2597992.48  | 628.38  | 334.49  | 30.46 | 32.42 | 35.39 | 27.08 | 898.99  | 1.30705 |
| 2646658.38  | 631.12  | 335.44  | 30.48 | 32.44 | 35.42 | 27.11 | 899.99  | 1.30671 |
| 2690565.91  | 633.56  | 336.29  | 30.49 | 32.46 | 35.45 | 27.14 | 900.88  | 1.30640 |
| 2730158.84  | 635.74  | 337.03  | 30.50 | 32.47 | 35.47 | 27.16 | 901.67  | 1.30614 |
| 2764097.81  | 637.58  | 337.67  | 30.51 | 32.49 | 35.49 | 27.18 | 902.34  | 1.30591 |
| 2792948.73  | 639.13  | 338.20  | 30.52 | 32.50 | 35.51 | 27.20 | 902.91  | 1.30572 |
| 2815426.72  | 640.33  | 338.61  | 30.53 | 32.51 | 35.52 | 27.21 | 903.34  | 1.30557 |
| 2831250.97  | 641.18  | 338.90  | 30.53 | 32.51 | 35.53 | 27.22 | 903.65  | 1.30547 |
| 2841220.31  | 641.70  | 339.08  | 30.54 | 32.52 | 35.54 | 27.22 | 903.84  | 1.30540 |
| 15595345.95 | 3522.28 | 1328.50 | 37.32 | 40.74 | 57.25 | 48.94 | 1624.67 | 1.16990 |
| 15575671.26 | 3521.64 | 1327.82 | 37.32 | 40.74 | 57.24 | 48.93 | 1624.31 | 1.16994 |
| 15526683.82 | 3520.02 | 1326.12 | 37.32 | 40.74 | 57.21 | 48.90 | 1623.43 | 1.17003 |
| 15448889.56 | 3517.46 | 1323.42 | 37.32 | 40.74 | 57.17 | 48.86 | 1622.01 | 1.17018 |
| 15338305.01 | 3513.78 | 1319.57 | 37.32 | 40.73 | 57.11 | 48.80 | 1620.00 | 1.17039 |
| 15196227.28 | 3509.03 | 1314.60 | 37.31 | 40.72 | 57.03 | 48.72 | 1617.41 | 1.17066 |
| 15028886.01 | 3503.37 | 1308.72 | 37.31 | 40.71 | 56.94 | 48.63 | 1614.33 | 1.17099 |
| 14837873.15 | 3496.83 | 1301.97 | 37.31 | 40.70 | 56.83 | 48.52 | 1610.80 | 1.17136 |
| 14620572.75 | 3489.29 | 1294.23 | 37.30 | 40.69 | 56.71 | 48.40 | 1606.75 | 1.17180 |
| 14379262.22 | 3480.79 | 1285.57 | 37.29 | 40.68 | 56.58 | 48.26 | 1602.22 | 1.17228 |
| 14120468.09 | 3471.51 | 1276.20 | 37.29 | 40.66 | 56.43 | 48.11 | 1597.31 | 1.17281 |
| 13846265.80 | 3461.49 | 1266.18 | 37.28 | 40.64 | 56.27 | 47.95 | 1592.06 | 1.17338 |
| 13554930.69 | 3450.63 | 1255.42 | 37.27 | 40.62 | 56.10 | 47.78 | 1586.42 | 1.17400 |
| 13252641.24 | 3439.12 | 1244.13 | 37.26 | 40.60 | 55.92 | 47.61 | 1580.49 | 1.17465 |
| 12941414.97 | 3426.99 | 1232.38 | 37.26 | 40.58 | 55.73 | 47.42 | 1574.32 | 1.17534 |
| 12619847.32 | 3414.15 | 1220.09 | 37.25 | 40.56 | 55.54 | 47.23 | 1567.86 | 1.17606 |
| 12293432.38 | 3400.78 | 1207.46 | 37.24 | 40.54 | 55.34 | 47.03 | 1561.21 | 1.17681 |
| 11963891.26 | 3386.92 | 1194.54 | 37.23 | 40.52 | 55.13 | 46.82 | 1554.41 | 1.17758 |
| 11635698.44 | 3372.75 | 1181.50 | 37.22 | 40.49 | 54.93 | 46.61 | 1547.54 | 1.17837 |
| 11304403.60 | 3358.03 | 1168.16 | 37.21 | 40.47 | 54.72 | 46.40 | 1540.50 | 1.17919 |
| 10974361.87 | 3342.95 | 1154.69 | 37.20 | 40.44 | 54.50 | 46.19 | 1533.38 | 1.18002 |
| 10646758.53 | 3327.53 | 1141.13 | 37.18 | 40.41 | 54.29 | 45.97 | 1526.21 | 1.18086 |
| 10324960.16 | 3311.92 | 1127.62 | 37.17 | 40.38 | 54.07 | 45.76 | 1519.06 | 1.18171 |
| 10007311.84 | 3296.05 | 1114.10 | 37.16 | 40.36 | 53.85 | 45.54 | 1511.89 | 1.18258 |
| 9694623.55  | 3279.93 | 1100.60 | 37.15 | 40.33 | 53.64 | 45.32 | 1504.73 | 1.18344 |
| 9387587.73  | 3263.61 | 1087.15 | 37.14 | 40.30 | 53.42 | 45.11 | 1497.59 | 1.18432 |
| 9088623.02  | 3247.21 | 1073.87 | 37.13 | 40.27 | 53.21 | 44.90 | 1490.53 | 1.18519 |
| 8797891.46  | 3230.76 | 1060.77 | 37.12 | 40.24 | 53.00 | 44.69 | 1483.55 | 1.18606 |
| 8513864.27  | 3214.17 | 1047.79 | 37.11 | 40.21 | 52.79 | 44.48 | 1476.63 | 1.18694 |
| 8238410.32  | 3197.56 | 1035.03 | 37.09 | 40.18 | 52.59 | 44.27 | 1469.82 | 1.18780 |
| 7971516.03  | 3180.96 | 1022.49 | 37.08 | 40.15 | 52.39 | 44.07 | 1463.12 | 1.18866 |
| 7711766.25  | 3164.27 | 1010.12 | 37.07 | 40.12 | 52.19 | 43.87 | 1456.51 | 1.18952 |
| 7461877.44  | 3147.71 | 998.06  | 37.06 | 40.09 | 51.99 | 43.68 | 1450.05 | 1.19036 |
| 7220287.91  | 3131.19 | 986.25  | 37.05 | 40.06 | 51.80 | 43.49 | 1443.71 | 1.19120 |
| 6986858.07  | 3114.71 | 974.68  | 37.04 | 40.03 | 51.61 | 43.30 | 1437.50 | 1.19202 |
| 6761428.35  | 3098.30 | 963.37  | 37.03 | 40.00 | 51.43 | 43.12 | 1431.41 | 1.19284 |
| 6543822.89  | 3081.96 | 952.31  | 37.02 | 39.97 | 51.25 | 42.94 | 1425.46 | 1.19365 |
| 6335757.79  | 3065.85 | 941.61  | 37.00 | 39.94 | 51.08 | 42.76 | 1419.69 | 1.19443 |
| 6134013.32  | 3049.74 | 931.10  | 36.99 | 39.91 | 50.91 | 42.59 | 1414.01 | 1.19521 |

|            |         |        |       |       |       |       |         |         |
|------------|---------|--------|-------|-------|-------|-------|---------|---------|
| 5941098.22 | 3033.86 | 920.94 | 36.98 | 39.88 | 50.74 | 42.43 | 1408.52 | 1.19598 |
| 5754923.71 | 3018.08 | 911.01 | 36.97 | 39.85 | 50.58 | 42.26 | 1403.14 | 1.19673 |
| 5576055.81 | 3002.45 | 901.37 | 36.96 | 39.82 | 50.42 | 42.11 | 1397.91 | 1.19746 |
| 5404175.75 | 2986.99 | 892.00 | 36.95 | 39.79 | 50.27 | 41.95 | 1392.82 | 1.19818 |
| 5238978.10 | 2971.69 | 882.89 | 36.94 | 39.76 | 50.12 | 41.80 | 1387.87 | 1.19889 |
| 5080808.54 | 2956.62 | 874.08 | 36.93 | 39.73 | 49.97 | 41.66 | 1383.07 | 1.19958 |
| 4928680.73 | 2941.70 | 865.52 | 36.92 | 39.70 | 49.83 | 41.52 | 1378.39 | 1.20026 |
| 4782333.66 | 2926.94 | 857.20 | 36.91 | 39.68 | 49.70 | 41.38 | 1373.84 | 1.20092 |
| 4642059.21 | 2912.40 | 849.15 | 36.90 | 39.65 | 49.56 | 41.25 | 1369.43 | 1.20157 |
| 4507020.45 | 2898.01 | 841.32 | 36.90 | 39.62 | 49.43 | 41.12 | 1365.14 | 1.20220 |
| 4377968.23 | 2883.89 | 833.77 | 36.89 | 39.59 | 49.31 | 40.99 | 1360.99 | 1.20282 |
| 4253615.75 | 2869.91 | 826.43 | 36.88 | 39.57 | 49.19 | 40.87 | 1356.95 | 1.20342 |
| 4134645.86 | 2856.18 | 819.34 | 36.87 | 39.54 | 49.07 | 40.76 | 1353.04 | 1.20401 |
| 4019906.02 | 2842.59 | 812.44 | 36.86 | 39.52 | 48.95 | 40.64 | 1349.24 | 1.20459 |
| 3910018.36 | 2829.24 | 805.78 | 36.85 | 39.49 | 48.84 | 40.53 | 1345.55 | 1.20515 |
| 3804702.88 | 2816.12 | 799.35 | 36.84 | 39.47 | 48.74 | 40.42 | 1341.98 | 1.20569 |
| 3702980.91 | 2803.13 | 793.08 | 36.84 | 39.44 | 48.63 | 40.32 | 1338.50 | 1.20623 |
| 3605741.22 | 2790.41 | 787.04 | 36.83 | 39.42 | 48.53 | 40.22 | 1335.14 | 1.20675 |
| 3512052.89 | 2777.85 | 781.18 | 36.82 | 39.39 | 48.43 | 40.12 | 1331.87 | 1.20725 |
| 3422061.82 | 2765.50 | 775.51 | 36.81 | 39.37 | 48.34 | 40.02 | 1328.70 | 1.20775 |
| 3335866.71 | 2753.39 | 770.04 | 36.80 | 39.34 | 48.24 | 39.93 | 1325.64 | 1.20823 |
| 3252673.97 | 2741.43 | 764.72 | 36.80 | 39.32 | 48.15 | 39.84 | 1322.65 | 1.20870 |
| 3172894.12 | 2729.70 | 759.59 | 36.79 | 39.30 | 48.07 | 39.75 | 1319.77 | 1.20915 |
| 3096070.44 | 2718.16 | 754.61 | 36.78 | 39.28 | 47.98 | 39.67 | 1316.96 | 1.20960 |
| 3022054.04 | 2706.78 | 749.78 | 36.77 | 39.25 | 47.90 | 39.59 | 1314.23 | 1.21003 |
| 2951182.15 | 2695.66 | 745.13 | 36.77 | 39.23 | 47.82 | 39.51 | 1311.60 | 1.21046 |
| 2882807.85 | 2684.69 | 740.61 | 36.76 | 39.21 | 47.74 | 39.43 | 1309.04 | 1.21087 |
| 2816811.85 | 2673.89 | 736.23 | 36.75 | 39.19 | 47.67 | 39.35 | 1306.54 | 1.21127 |
| 2753502.43 | 2663.31 | 731.99 | 36.75 | 39.17 | 47.60 | 39.28 | 1304.13 | 1.21166 |
| 2692522.07 | 2652.91 | 727.90 | 36.74 | 39.15 | 47.53 | 39.21 | 1301.79 | 1.21204 |
| 2633750.37 | 2642.68 | 723.92 | 36.73 | 39.13 | 47.46 | 39.14 | 1299.51 | 1.21241 |
| 2577261.41 | 2632.66 | 720.08 | 36.73 | 39.11 | 47.39 | 39.08 | 1297.31 | 1.21278 |
| 2522749.49 | 2622.81 | 716.36 | 36.72 | 39.09 | 47.33 | 39.01 | 1295.16 | 1.21313 |
| 2470290.12 | 2613.14 | 712.75 | 36.71 | 39.07 | 47.26 | 38.95 | 1293.08 | 1.21347 |
| 2419606.82 | 2603.63 | 709.26 | 36.71 | 39.05 | 47.20 | 38.89 | 1291.06 | 1.21380 |
| 2370775.46 | 2594.30 | 705.87 | 36.70 | 39.04 | 47.14 | 38.83 | 1289.09 | 1.21413 |
| 2323699.58 | 2585.14 | 702.59 | 36.69 | 39.02 | 47.09 | 38.77 | 1287.19 | 1.21445 |
| 2278289.19 | 2576.14 | 699.40 | 36.69 | 39.00 | 47.03 | 38.72 | 1285.33 | 1.21476 |
| 2234460.26 | 2567.31 | 696.32 | 36.68 | 38.98 | 46.98 | 38.66 | 1283.53 | 1.21506 |
| 2192134.21 | 2558.64 | 693.33 | 36.67 | 38.97 | 46.92 | 38.61 | 1281.77 | 1.21535 |
| 2151371.97 | 2550.14 | 690.43 | 36.67 | 38.95 | 46.87 | 38.56 | 1280.07 | 1.21564 |
| 2111961.34 | 2541.79 | 687.62 | 36.66 | 38.93 | 46.82 | 38.51 | 1278.42 | 1.21592 |
| 2073964.17 | 2533.61 | 684.90 | 36.66 | 38.92 | 46.77 | 38.46 | 1276.81 | 1.21619 |
| 2037186.53 | 2525.56 | 682.26 | 36.65 | 38.90 | 46.73 | 38.41 | 1275.24 | 1.21646 |
| 2001808.55 | 2517.70 | 679.71 | 36.64 | 38.89 | 46.68 | 38.37 | 1273.72 | 1.21671 |
| 1967527.03 | 2509.97 | 677.22 | 36.64 | 38.87 | 46.64 | 38.32 | 1272.24 | 1.21697 |
| 1934293.43 | 2502.36 | 674.80 | 36.63 | 38.85 | 46.59 | 38.28 | 1270.80 | 1.21721 |
| 1902277.20 | 2494.92 | 672.47 | 36.63 | 38.84 | 46.55 | 38.24 | 1269.40 | 1.21745 |
| 1871416.18 | 2487.64 | 670.21 | 36.62 | 38.83 | 46.51 | 38.19 | 1268.04 | 1.21769 |
| 1841449.38 | 2480.47 | 668.00 | 36.62 | 38.81 | 46.47 | 38.15 | 1266.71 | 1.21791 |
| 1812536.95 | 2473.46 | 665.87 | 36.61 | 38.80 | 46.43 | 38.12 | 1265.42 | 1.21814 |
| 1784531.47 | 2466.57 | 663.79 | 36.61 | 38.78 | 46.39 | 38.08 | 1264.16 | 1.21835 |

|            |         |        |       |       |       |       |         |         |
|------------|---------|--------|-------|-------|-------|-------|---------|---------|
| 1757392.48 | 2459.80 | 661.78 | 36.60 | 38.77 | 46.36 | 38.04 | 1262.94 | 1.21857 |
| 1731172.64 | 2453.18 | 659.82 | 36.60 | 38.76 | 46.32 | 38.01 | 1261.75 | 1.21877 |
| 1705828.81 | 2446.69 | 657.93 | 36.59 | 38.74 | 46.28 | 37.97 | 1260.59 | 1.21897 |
| 1681320.51 | 2440.34 | 656.09 | 36.58 | 38.73 | 46.25 | 37.94 | 1259.46 | 1.21917 |
| 1657525.81 | 2434.10 | 654.30 | 36.58 | 38.72 | 46.22 | 37.90 | 1258.36 | 1.21936 |
| 1634496.97 | 2427.98 | 652.56 | 36.57 | 38.71 | 46.19 | 37.87 | 1257.29 | 1.21955 |
| 1612200.05 | 2421.98 | 650.87 | 36.57 | 38.70 | 46.15 | 37.84 | 1256.25 | 1.21973 |
| 1590603.05 | 2416.10 | 649.23 | 36.56 | 38.68 | 46.12 | 37.81 | 1255.23 | 1.21991 |
| 1569751.82 | 2410.36 | 647.64 | 36.56 | 38.67 | 46.09 | 37.78 | 1254.24 | 1.22008 |
| 1549464.09 | 2404.71 | 646.09 | 36.56 | 38.66 | 46.06 | 37.75 | 1253.28 | 1.22025 |
| 1529863.39 | 2399.20 | 644.59 | 36.55 | 38.65 | 46.04 | 37.72 | 1252.34 | 1.22042 |
| 1510848.51 | 2393.78 | 643.13 | 36.55 | 38.64 | 46.01 | 37.69 | 1251.42 | 1.22058 |
| 1492395.60 | 2388.47 | 641.71 | 36.54 | 38.63 | 45.98 | 37.67 | 1250.53 | 1.22073 |
| 1474549.98 | 2383.28 | 640.34 | 36.54 | 38.62 | 45.96 | 37.64 | 1249.66 | 1.22089 |
| 1457219.50 | 2378.19 | 639.00 | 36.53 | 38.61 | 45.93 | 37.62 | 1248.82 | 1.22104 |
| 1440449.16 | 2373.21 | 637.70 | 36.53 | 38.60 | 45.91 | 37.59 | 1247.99 | 1.22118 |
| 1424152.14 | 2368.33 | 636.43 | 36.52 | 38.59 | 45.88 | 37.57 | 1247.19 | 1.22133 |
| 1408372.97 | 2363.55 | 635.20 | 36.52 | 38.58 | 45.86 | 37.54 | 1246.40 | 1.22147 |
| 1393029.66 | 2358.86 | 634.00 | 36.52 | 38.57 | 45.83 | 37.52 | 1245.64 | 1.22160 |
| 1378166.22 | 2354.27 | 632.84 | 36.51 | 38.56 | 45.81 | 37.50 | 1244.89 | 1.22173 |
| 1363763.94 | 2349.79 | 631.71 | 36.51 | 38.55 | 45.79 | 37.48 | 1244.17 | 1.22186 |
| 1349805.11 | 2345.40 | 630.61 | 36.50 | 38.54 | 45.77 | 37.45 | 1243.46 | 1.22199 |
| 1336272.96 | 2341.11 | 629.54 | 36.50 | 38.53 | 45.75 | 37.43 | 1242.77 | 1.22211 |
| 1323095.75 | 2336.90 | 628.50 | 36.50 | 38.53 | 45.73 | 37.41 | 1242.10 | 1.22223 |
| 1310370.99 | 2332.80 | 627.50 | 36.49 | 38.52 | 45.71 | 37.39 | 1241.44 | 1.22235 |
| 1297973.61 | 2328.77 | 626.51 | 36.49 | 38.51 | 45.69 | 37.37 | 1240.80 | 1.22246 |
| 1285998.71 | 2324.84 | 625.56 | 36.48 | 38.50 | 45.67 | 37.36 | 1240.18 | 1.22258 |
| 1274326.38 | 2320.99 | 624.63 | 36.48 | 38.49 | 45.65 | 37.34 | 1239.58 | 1.22268 |
| 1263049.42 | 2317.23 | 623.73 | 36.48 | 38.49 | 45.63 | 37.32 | 1238.99 | 1.22279 |
| 1252052.63 | 2313.54 | 622.85 | 36.47 | 38.48 | 45.62 | 37.30 | 1238.41 | 1.22289 |
| 1241426.64 | 2309.95 | 622.00 | 36.47 | 38.47 | 45.60 | 37.29 | 1237.85 | 1.22300 |
| 1231109.56 | 2306.44 | 621.18 | 36.47 | 38.46 | 45.58 | 37.27 | 1237.30 | 1.22309 |
| 1221091.25 | 2303.01 | 620.37 | 36.46 | 38.46 | 45.57 | 37.25 | 1236.77 | 1.22319 |
| 1211362.10 | 2299.65 | 619.59 | 36.46 | 38.45 | 45.55 | 37.24 | 1236.25 | 1.22328 |
| 1201959.83 | 2296.38 | 618.83 | 36.46 | 38.44 | 45.54 | 37.22 | 1235.75 | 1.22337 |
| 1192781.20 | 2293.17 | 618.09 | 36.45 | 38.44 | 45.52 | 37.21 | 1235.26 | 1.22346 |
| 1183911.08 | 2290.04 | 617.37 | 36.45 | 38.43 | 45.51 | 37.19 | 1234.78 | 1.22355 |
| 1175339.68 | 2287.00 | 616.68 | 36.45 | 38.43 | 45.49 | 37.18 | 1234.31 | 1.22363 |
| 1166968.75 | 2284.02 | 616.00 | 36.44 | 38.42 | 45.48 | 37.17 | 1233.86 | 1.22372 |
| 1158880.63 | 2281.12 | 615.34 | 36.44 | 38.41 | 45.47 | 37.15 | 1233.42 | 1.22380 |
| 1151023.42 | 2278.28 | 614.70 | 36.44 | 38.41 | 45.45 | 37.14 | 1232.99 | 1.22387 |
| 1143433.43 | 2275.52 | 614.09 | 36.44 | 38.40 | 45.44 | 37.13 | 1232.57 | 1.22395 |
| 1136060.53 | 2272.83 | 613.48 | 36.43 | 38.40 | 45.43 | 37.11 | 1232.16 | 1.22402 |
| 1128898.76 | 2270.20 | 612.90 | 36.43 | 38.39 | 45.42 | 37.10 | 1231.77 | 1.22410 |
| 1121983.86 | 2267.65 | 612.33 | 36.43 | 38.39 | 45.41 | 37.09 | 1231.38 | 1.22417 |
| 1115268.07 | 2265.16 | 611.78 | 36.42 | 38.38 | 45.39 | 37.08 | 1231.01 | 1.22423 |
| 1108746.22 | 2262.73 | 611.25 | 36.42 | 38.38 | 45.38 | 37.07 | 1230.65 | 1.22430 |
| 1102453.47 | 2260.37 | 610.73 | 36.42 | 38.37 | 45.37 | 37.06 | 1230.29 | 1.22436 |
| 1096344.17 | 2258.07 | 610.23 | 36.42 | 38.37 | 45.36 | 37.05 | 1229.95 | 1.22443 |
| 1090453.14 | 2255.84 | 609.74 | 36.41 | 38.36 | 45.35 | 37.04 | 1229.62 | 1.22449 |
| 1084735.98 | 2253.67 | 609.27 | 36.41 | 38.36 | 45.34 | 37.03 | 1229.30 | 1.22455 |
| 1079227.21 | 2251.56 | 608.82 | 36.41 | 38.35 | 45.33 | 37.02 | 1228.99 | 1.22460 |

|            |         |        |       |       |       |       |         |         |
|------------|---------|--------|-------|-------|-------|-------|---------|---------|
| 1073883.60 | 2249.52 | 608.38 | 36.41 | 38.35 | 45.32 | 37.01 | 1228.68 | 1.22466 |
| 1068739.36 | 2247.54 | 607.95 | 36.41 | 38.35 | 45.31 | 37.00 | 1228.39 | 1.22471 |
| 1063752.34 | 2245.61 | 607.54 | 36.40 | 38.34 | 45.31 | 36.99 | 1228.10 | 1.22476 |
| 1058919.15 | 2243.73 | 607.14 | 36.40 | 38.34 | 45.30 | 36.98 | 1227.83 | 1.22482 |
| 1054273.54 | 2241.92 | 606.75 | 36.40 | 38.33 | 45.29 | 36.98 | 1227.56 | 1.22486 |
| 1049774.83 | 2240.16 | 606.38 | 36.40 | 38.33 | 45.28 | 36.97 | 1227.30 | 1.22491 |
| 1045456.51 | 2238.47 | 606.02 | 36.40 | 38.33 | 45.27 | 36.96 | 1227.05 | 1.22496 |
| 1041314.97 | 2236.84 | 605.68 | 36.39 | 38.32 | 45.27 | 36.95 | 1226.82 | 1.22500 |
| 1037310.81 | 2235.25 | 605.34 | 36.39 | 38.32 | 45.26 | 36.95 | 1226.58 | 1.22504 |
| 1033441.51 | 2233.72 | 605.02 | 36.39 | 38.32 | 45.25 | 36.94 | 1226.36 | 1.22508 |
| 1029740.09 | 2232.25 | 604.71 | 36.39 | 38.31 | 45.25 | 36.93 | 1226.14 | 1.22512 |
| 1026168.31 | 2230.82 | 604.42 | 36.39 | 38.31 | 45.24 | 36.93 | 1225.94 | 1.22516 |
| 1022759.00 | 2229.46 | 604.13 | 36.39 | 38.31 | 45.24 | 36.92 | 1225.74 | 1.22520 |
| 1019474.62 | 2228.14 | 603.86 | 36.38 | 38.31 | 45.23 | 36.91 | 1225.55 | 1.22523 |
| 1016347.81 | 2226.88 | 603.59 | 36.38 | 38.30 | 45.22 | 36.91 | 1225.36 | 1.22527 |
| 1013341.66 | 2225.67 | 603.34 | 36.38 | 38.30 | 45.22 | 36.90 | 1225.19 | 1.22530 |
| 1010488.67 | 2224.52 | 603.10 | 36.38 | 38.30 | 45.21 | 36.90 | 1225.02 | 1.22533 |
| 1007786.63 | 2223.42 | 602.88 | 36.38 | 38.30 | 45.21 | 36.89 | 1224.86 | 1.22536 |
| 1005199.49 | 2222.37 | 602.66 | 36.38 | 38.29 | 45.20 | 36.89 | 1224.71 | 1.22539 |
| 1002725.75 | 2221.36 | 602.45 | 36.38 | 38.29 | 45.20 | 36.89 | 1224.56 | 1.22542 |
| 1000397.65 | 2220.41 | 602.26 | 36.38 | 38.29 | 45.20 | 36.88 | 1224.42 | 1.22544 |
| 998179.90  | 2219.51 | 602.07 | 36.37 | 38.29 | 45.19 | 36.88 | 1224.29 | 1.22546 |
| 996104.64  | 2218.66 | 601.90 | 36.37 | 38.29 | 45.19 | 36.87 | 1224.17 | 1.22549 |
| 994137.02  | 2217.85 | 601.73 | 36.37 | 38.28 | 45.18 | 36.87 | 1224.05 | 1.22551 |
| 992309.11  | 2217.10 | 601.58 | 36.37 | 38.28 | 45.18 | 36.87 | 1223.95 | 1.22553 |
| 990619.56  | 2216.41 | 601.44 | 36.37 | 38.28 | 45.18 | 36.86 | 1223.85 | 1.22555 |
| 989034.14  | 2215.75 | 601.30 | 36.37 | 38.28 | 45.18 | 36.86 | 1223.75 | 1.22556 |
| 987551.97  | 2215.14 | 601.18 | 36.37 | 38.28 | 45.17 | 36.86 | 1223.66 | 1.22558 |
| 986205.03  | 2214.58 | 601.07 | 36.37 | 38.28 | 45.17 | 36.86 | 1223.58 | 1.22560 |
| 984992.35  | 2214.08 | 600.96 | 36.37 | 38.28 | 45.17 | 36.85 | 1223.51 | 1.22561 |
| 983880.37  | 2213.62 | 600.87 | 36.37 | 38.28 | 45.17 | 36.85 | 1223.44 | 1.22562 |
| 982901.09  | 2213.22 | 600.79 | 36.37 | 38.28 | 45.16 | 36.85 | 1223.39 | 1.22563 |
| 982021.24  | 2212.85 | 600.71 | 36.37 | 38.27 | 45.16 | 36.85 | 1223.33 | 1.22564 |
| 981240.35  | 2212.53 | 600.65 | 36.37 | 38.27 | 45.16 | 36.85 | 1223.29 | 1.22565 |
| 980622.94  | 2212.27 | 600.59 | 36.37 | 38.27 | 45.16 | 36.85 | 1223.25 | 1.22566 |
| 980071.11  | 2212.04 | 600.55 | 36.37 | 38.27 | 45.16 | 36.84 | 1223.22 | 1.22566 |
| 979681.92  | 2211.88 | 600.52 | 36.37 | 38.27 | 45.16 | 36.84 | 1223.19 | 1.22567 |
| 132100.00  | 2211.76 | 600.49 | 36.37 | 38.27 | 45.16 | 36.84 | 1223.18 | 1.22567 |

## 6.8 Example of PV data, Temperature, and Specific Heat calculations

| Crank Angle | Volume         | 1000RPM                   |                     |                        |                     |                       |                    |                    |          |           |
|-------------|----------------|---------------------------|---------------------|------------------------|---------------------|-----------------------|--------------------|--------------------|----------|-----------|
|             |                | Average Cylinder Pressure | Average Temperature | Cp Average - Isooctane | Cp Average - Oxygen | Cp Average - Nitrogen | Cp Average Overall | Cv Average Overall | $\gamma$ | Work Done |
| Degrees     | m <sup>3</sup> | Pascals                   | Kelvin              | KJ/Kmol.K              | KJ/Kmol.K           | KJ/Kmol.K             | KJ/Kmol.K          | KJ/Kmol.K          |          | J         |
| -360        | 0.00004        | 128100.00000              | 26.47013            | -167.30108             | 25.78706            | 28.81375              | 25.26809           | 16.95362           | 1.49042  |           |
| -359        | 0.00004        | 128233.33333              | 26.52629            | -166.47789             | 25.78791            | 28.81362              | 25.28042           | 16.96595           | 1.49007  | 0.00513   |
| -358        | 0.00004        | 128700.00000              | 26.69460            | -164.04020             | 25.79048            | 28.81324              | 25.31694           | 17.00246           | 1.48902  | 0.01285   |
| -357        | 0.00004        | 129033.33333              | 26.87888            | -161.42094             | 25.79329            | 28.81282              | 25.35618           | 17.04171           | 1.48789  | 0.02062   |
| -356        | 0.00004        | 129200.00000              | 27.07933            | -158.62925             | 25.79634            | 28.81236              | 25.39801           | 17.08354           | 1.48669  | 0.02970   |
| -355        | 0.00004        | 129366.66667              | 27.33072            | -155.21013             | 25.80017            | 28.81179              | 25.44926           | 17.13479           | 1.48524  | 0.03879   |
| -354        | 0.00004        | 129533.33333              | 27.62601            | -151.30611             | 25.80467            | 28.81113              | 25.50778           | 17.19331           | 1.48359  | 0.04660   |
| -353        | 0.00004        | 129866.66667              | 28.00130            | -146.51165             | 25.81038            | 28.81028              | 25.57968           | 17.26520           | 1.48157  | 0.05447   |
| -352        | 0.00004        | 130033.33333              | 28.39260            | -141.70236             | 25.81634            | 28.80940              | 25.65181           | 17.33734           | 1.47957  | 0.06368   |
| -351        | 0.00004        | 130033.33333              | 28.79873            | -136.90447             | 25.82252            | 28.80850              | 25.72381           | 17.40933           | 1.47759  | 0.07282   |
| -350        | 0.00004        | 130200.00000              | 29.28585            | -131.39474             | 25.82992            | 28.80742              | 25.80651           | 17.49204           | 1.47533  | 0.08067   |
| -349        | 0.00004        | 130366.66667              | 29.81776            | -125.66459             | 25.83801            | 28.80624              | 25.89257           | 17.57810           | 1.47300  | 0.08859   |
| -348        | 0.00004        | 130200.00000              | 30.32426            | -120.46728             | 25.84570            | 28.80513              | 25.97066           | 17.65619           | 1.47091  | 0.09771   |
| -347        | 0.00004        | 130366.66667              | 30.95201            | -114.35155             | 25.85523            | 28.80377              | 26.06261           | 17.74813           | 1.46847  | 0.10553   |
| -346        | 0.00004        | 130200.00000              | 31.54420            | -108.88911             | 25.86421            | 28.80249              | 26.14478           | 17.83031           | 1.46631  | 0.11335   |
| -345        | 0.00004        | 130200.00000              | 32.22678            | -102.93348             | 25.87455            | 28.80102              | 26.23443           | 17.91996           | 1.46398  | 0.12239   |
| -344        | 0.00005        | 129700.00000              | 32.82639            | -97.98019              | 25.88364            | 28.79974              | 26.30905           | 17.99458           | 1.46205  | 0.12995   |
| -343        | 0.00005        | 129366.66667              | 33.50683            | -92.65020              | 25.89393            | 28.79831              | 26.38940           | 18.07493           | 1.46000  | 0.13731   |
| -342        | 0.00005        | 129200.00000              | 34.26350            | -87.05781              | 25.90538            | 28.79672              | 26.47378           | 18.15931           | 1.45786  | 0.14350   |
| -341        | 0.00005        | 129200.00000              | 35.11378            | -81.15823              | 25.91822            | 28.79496              | 26.56289           | 18.24842           | 1.45563  | 0.15246   |
| -340        | 0.00005        | 129200.00000              | 36.00730            | -75.35721              | 25.93171            | 28.79312              | 26.65060           | 18.33613           | 1.45345  | 0.16021   |
| -339        | 0.00005        | 128866.66667              | 36.84874            | -70.23326              | 25.94440            | 28.79142              | 26.72817           | 18.41370           | 1.45154  | 0.16774   |
| -338        | 0.00005        | 128866.66667              | 37.81901            | -64.69451              | 25.95902            | 28.78947              | 26.81213           | 18.49766           | 1.44949  | 0.17397   |
| -337        | 0.00005        | 128700.00000              | 38.78218            | -59.55116              | 25.97351            | 28.78756              | 26.89021           | 18.57574           | 1.44760  | 0.18158   |
| -336        | 0.00006        | 128700.00000              | 39.83733            | -54.28246              | 25.98937            | 28.78550              | 26.97031           | 18.65584           | 1.44568  | 0.18919   |
| -335        | 0.00006        | 128566.66667              | 40.89314            | -49.35554              | 26.00523            | 28.78346              | 27.04535           | 18.73088           | 1.44389  | 0.19681   |
| -334        | 0.00006        | 128433.33333              | 41.98249            | -44.59770              | 26.02156            | 28.78139              | 27.11794           | 18.80347           | 1.44218  | 0.20303   |
| -333        | 0.00006        | 128566.66667              | 43.19486            | -39.65170              | 26.03972            | 28.77912              | 27.19355           | 18.87908           | 1.44041  | 0.20946   |
| -332        | 0.00006        | 128566.66667              | 44.40667            | -35.03742              | 26.05784            | 28.77689              | 27.26425           | 18.94978           | 1.43876  | 0.21728   |
| -331        | 0.00006        | 128700.00000              | 45.70167            | -30.43158              | 26.07719            | 28.77454              | 27.33499           | 19.02052           | 1.43713  | 0.22382   |
| -330        | 0.00007        | 128866.66667              | 47.04736            | -25.96331              | 26.09725            | 28.77215              | 27.40380           | 19.08932           | 1.43556  | 0.23052   |
| -329        | 0.00007        | 128866.66667              | 48.37699            | -21.83234              | 26.11705            | 28.76983              | 27.46758           | 19.15311           | 1.43411  | 0.23840   |
| -328        | 0.00007        | 129200.00000              | 49.86402            | -17.51024              | 26.13916            | 28.76729              | 27.53452           | 19.22004           | 1.43259  | 0.24387   |
| -327        | 0.00007        | 129366.66667              | 51.32807            | -13.52870              | 26.16090            | 28.76484              | 27.59638           | 19.28190           | 1.43121  | 0.25081   |
| -326        | 0.00007        | 129533.33333              | 52.83185            | -9.69076               | 26.18318            | 28.76238              | 27.65620           | 19.34173           | 1.42987  | 0.25761   |
| -325        | 0.00008        | 129533.33333              | 54.30562            | -6.15042               | 26.20498            | 28.76002              | 27.71158           | 19.39711           | 1.42864  | 0.26425   |
| -324        | 0.00008        | 129533.33333              | 55.81552            | -2.72638               | 26.22728            | 28.75766              | 27.76533           | 19.45086           | 1.42746  | 0.27072   |
| -323        | 0.00008        | 129533.33333              | 57.34708            | 0.55838                | 26.24987            | 28.75533              | 27.81708           | 19.50261           | 1.42633  | 0.27461   |
| -322        | 0.00008        | 129533.33333              | 58.92200            | 3.75840                | 26.27305            | 28.75299              | 27.86769           | 19.55322           | 1.42522  | 0.28238   |
| -321        | 0.00008        | 129533.33333              | 60.51858            | 6.83715                | 26.29651            | 28.75067              | 27.91657           | 19.60210           | 1.42416  | 0.28627   |
| -320        | 0.00009        | 129200.00000              | 61.99136            | 9.54394                | 26.31811            | 28.74859              | 27.95972           | 19.64525           | 1.42323  | 0.29237   |
| -319        | 0.00009        | 129033.33333              | 63.56658            | 12.31100               | 26.34117            | 28.74643              | 28.00399           | 19.68952           | 1.42228  | 0.29697   |
| -318        | 0.00009        | 129033.33333              | 65.25056            | 15.13650               | 26.36579            | 28.74418              | 28.04940           | 19.73493           | 1.42131  | 0.30194   |

|      |         |              |           |           |          |          |          |          |         |         |
|------|---------|--------------|-----------|-----------|----------|----------|----------|----------|---------|---------|
| -317 | 0.00009 | 129033.33333 | 66.96332  | 17.88327  | 26.39077 | 28.74196 | 28.09373 | 19.77926 | 1.42036 | 0.30710 |
| -316 | 0.00010 | 129033.33333 | 68.69768  | 20.54673  | 26.41603 | 28.73979 | 28.13691 | 19.82244 | 1.41945 | 0.31097 |
| -315 | 0.00010 | 129033.33333 | 70.46082  | 23.14436  | 26.44165 | 28.73765 | 28.17922 | 19.86475 | 1.41855 | 0.31613 |
| -314 | 0.00010 | 129033.33333 | 72.25274  | 25.68146  | 26.46763 | 28.73555 | 28.22073 | 19.90626 | 1.41768 | 0.32129 |
| -313 | 0.00010 | 129200.00000 | 74.16192  | 28.28121  | 26.49527 | 28.73340 | 28.26347 | 19.94900 | 1.41679 | 0.32537 |
| -312 | 0.00011 | 129200.00000 | 76.00660  | 30.70129  | 26.52191 | 28.73141 | 28.30346 | 19.98899 | 1.41595 | 0.33075 |
| -311 | 0.00011 | 129366.66667 | 77.96614  | 33.18246  | 26.55015 | 28.72937 | 28.34465 | 20.03018 | 1.41510 | 0.33355 |
| -310 | 0.00011 | 129366.66667 | 79.85649  | 35.49651  | 26.57733 | 28.72750 | 28.38327 | 20.06879 | 1.41430 | 0.33894 |
| -309 | 0.00011 | 129533.33333 | 81.86661  | 37.87929  | 26.60617 | 28.72559 | 28.42322 | 20.10875 | 1.41348 | 0.34175 |
| -308 | 0.00012 | 129533.33333 | 83.80274  | 40.10519  | 26.63389 | 28.72385 | 28.46073 | 20.14626 | 1.41271 | 0.34715 |
| -307 | 0.00012 | 129533.33333 | 85.75332  | 42.28501  | 26.66176 | 28.72217 | 28.49765 | 20.18318 | 1.41195 | 0.34974 |
| -306 | 0.00012 | 129200.00000 | 87.49262  | 44.17994  | 26.68655 | 28.72076 | 28.52988 | 20.21541 | 1.41129 | 0.35188 |
| -305 | 0.00012 | 129200.00000 | 89.48142  | 46.29481  | 26.71485 | 28.71922 | 28.56602 | 20.25155 | 1.41056 | 0.35659 |
| -304 | 0.00013 | 129200.00000 | 91.47742  | 48.36605  | 26.74318 | 28.71777 | 28.60159 | 20.28712 | 1.40984 | 0.35788 |
| -303 | 0.00013 | 129200.00000 | 93.49504  | 50.41164  | 26.77175 | 28.71639 | 28.63688 | 20.32241 | 1.40913 | 0.36176 |
| -302 | 0.00013 | 129066.66667 | 95.42849  | 52.33004  | 26.79908 | 28.71516 | 28.67013 | 20.35566 | 1.40846 | 0.36416 |
| -301 | 0.00014 | 128900.00000 | 97.33976  | 54.18915  | 26.82602 | 28.71402 | 28.70250 | 20.38803 | 1.40781 | 0.36502 |
| -300 | 0.00014 | 128733.33333 | 99.26731  | 56.02923  | 26.85315 | 28.71296 | 28.73467 | 20.42020 | 1.40717 | 0.36842 |
| -299 | 0.00014 | 128733.33333 | 101.32790 | 57.96030  | 26.88207 | 28.71191 | 28.76859 | 20.45412 | 1.40649 | 0.36946 |
| -298 | 0.00014 | 128733.33333 | 103.40285 | 59.86991  | 26.91113 | 28.71095 | 28.80229 | 20.48781 | 1.40583 | 0.37204 |
| -297 | 0.00015 | 128566.66667 | 105.35558 | 61.63724  | 26.93842 | 28.71014 | 28.83361 | 20.51913 | 1.40521 | 0.37437 |
| -296 | 0.00015 | 128566.66667 | 107.44219 | 63.49597  | 26.96751 | 28.70936 | 28.86669 | 20.55222 | 1.40455 | 0.37413 |
| -295 | 0.00015 | 128433.33333 | 109.42953 | 65.23954  | 26.99516 | 28.70870 | 28.89785 | 20.58338 | 1.40394 | 0.37651 |
| -294 | 0.00016 | 128266.66667 | 111.39787 | 66.94236  | 27.02248 | 28.70814 | 28.92842 | 20.61394 | 1.40334 | 0.37863 |
| -293 | 0.00016 | 128266.66667 | 113.50822 | 68.74307  | 27.05170 | 28.70763 | 28.96087 | 20.64640 | 1.40271 | 0.37839 |
| -292 | 0.00016 | 128266.66667 | 115.62573 | 70.52552  | 27.08095 | 28.70721 | 28.99313 | 20.67866 | 1.40208 | 0.37967 |
| -291 | 0.00016 | 128266.66667 | 117.75039 | 72.29097  | 27.11023 | 28.70689 | 29.02522 | 20.71075 | 1.40146 | 0.38095 |
| -290 | 0.00017 | 128266.66667 | 119.87504 | 74.03475  | 27.13944 | 28.70666 | 29.05704 | 20.74257 | 1.40084 | 0.38095 |
| -289 | 0.00017 | 128266.66667 | 122.00685 | 75.76388  | 27.16868 | 28.70653 | 29.08873 | 20.77426 | 1.40023 | 0.38223 |
| -288 | 0.00017 | 128433.33333 | 124.29997 | 77.60225  | 27.20005 | 28.70649 | 29.12256 | 20.80809 | 1.39958 | 0.38248 |
| -287 | 0.00018 | 128266.66667 | 126.27763 | 79.17073  | 27.22704 | 28.70655 | 29.15154 | 20.83707 | 1.39902 | 0.38377 |
| -286 | 0.00018 | 128600.00000 | 128.75032 | 81.11094  | 27.26070 | 28.70673 | 29.18753 | 20.87306 | 1.39834 | 0.38402 |
| -285 | 0.00018 | 128433.33333 | 130.72520 | 82.64476  | 27.28752 | 28.70697 | 29.21610 | 20.90163 | 1.39779 | 0.38426 |
| -284 | 0.00019 | 128400.00000 | 132.83246 | 84.26672  | 27.31607 | 28.70732 | 29.24642 | 20.93195 | 1.39721 | 0.38397 |
| -283 | 0.00019 | 128100.00000 | 134.65829 | 85.66038  | 27.34075 | 28.70769 | 29.27256 | 20.95809 | 1.39672 | 0.38347 |
| -282 | 0.00019 | 128100.00000 | 136.79448 | 87.27779  | 27.36956 | 28.70821 | 29.30301 | 20.98853 | 1.39614 | 0.38302 |
| -281 | 0.00019 | 128100.00000 | 138.92352 | 88.87631  | 27.39820 | 28.70882 | 29.33321 | 21.01873 | 1.39557 | 0.38174 |
| -280 | 0.00020 | 127766.66667 | 140.68552 | 90.18952  | 27.42186 | 28.70940 | 29.35810 | 21.04362 | 1.39511 | 0.38124 |
| -279 | 0.00020 | 127933.33333 | 142.98818 | 91.89294  | 27.45270 | 28.71024 | 29.39049 | 21.07602 | 1.39450 | 0.37971 |
| -278 | 0.00020 | 127600.00000 | 144.72923 | 93.17171  | 27.47597 | 28.71095 | 29.41490 | 21.10042 | 1.39404 | 0.37947 |
| -277 | 0.00021 | 127766.66667 | 147.02040 | 94.84294  | 27.50652 | 28.71198 | 29.44689 | 21.13242 | 1.39345 | 0.37667 |
| -276 | 0.00021 | 127766.66667 | 149.12252 | 96.36516  | 27.53447 | 28.71301 | 29.47614 | 21.16167 | 1.39290 | 0.37691 |
| -275 | 0.00021 | 127766.66667 | 151.22464 | 97.87715  | 27.56236 | 28.71413 | 29.50529 | 21.19082 | 1.39236 | 0.37691 |
| -274 | 0.00022 | 127766.66667 | 153.31252 | 99.36915  | 27.59000 | 28.71533 | 29.53415 | 21.21968 | 1.39183 | 0.37436 |
| -273 | 0.00022 | 127766.66667 | 155.38614 | 100.84170 | 27.61738 | 28.71660 | 29.56273 | 21.24826 | 1.39130 | 0.37180 |
| -272 | 0.00022 | 128100.00000 | 157.87056 | 102.59427 | 27.65010 | 28.71824 | 29.59686 | 21.28239 | 1.39067 | 0.37229 |
| -271 | 0.00022 | 128266.66667 | 160.14339 | 104.18682 | 27.67996 | 28.71984 | 29.62799 | 21.31352 | 1.39010 | 0.37045 |
| -270 | 0.00023 | 128266.66667 | 162.20366 | 105.62186 | 27.70695 | 28.72137 | 29.65614 | 21.34166 | 1.38959 | 0.36941 |
| -269 | 0.00023 | 128433.33333 | 164.47021 | 107.19147 | 27.73658 | 28.72316 | 29.68702 | 21.37255 | 1.38903 | 0.36836 |
| -268 | 0.00023 | 128433.33333 | 166.51167 | 108.59731 | 27.76320 | 28.72485 | 29.71477 | 21.40030 | 1.38852 | 0.36604 |
| -267 | 0.00024 | 128566.66667 | 168.71378 | 110.10562 | 27.79184 | 28.72676 | 29.74463 | 21.43016 | 1.38798 | 0.36365 |
| -266 | 0.00024 | 128733.33333 | 170.95000 | 111.62892 | 27.82085 | 28.72879 | 29.77490 | 21.46042 | 1.38743 | 0.36151 |

|      |         |              |           |           |          |          |          |          |         |         |
|------|---------|--------------|-----------|-----------|----------|----------|----------|----------|---------|---------|
| -265 | 0.00024 | 128733.33333 | 172.96033 | 112.99133 | 27.84687 | 28.73070 | 29.80204 | 21.48757 | 1.38694 | 0.36045 |
| -264 | 0.00024 | 128733.33333 | 174.95630 | 114.33761 | 27.87265 | 28.73266 | 29.82895 | 21.51448 | 1.38646 | 0.35788 |
| -263 | 0.00025 | 128733.33333 | 176.93792 | 115.66807 | 27.89818 | 28.73469 | 29.85562 | 21.54114 | 1.38598 | 0.35530 |
| -262 | 0.00025 | 128733.33333 | 178.90517 | 116.98299 | 27.92347 | 28.73677 | 29.88204 | 21.56757 | 1.38551 | 0.35273 |
| -261 | 0.00025 | 128400.00000 | 180.38260 | 117.96672 | 27.94242 | 28.73838 | 29.90186 | 21.58739 | 1.38515 | 0.34842 |
| -260 | 0.00025 | 128566.66667 | 182.55277 | 119.40593 | 27.97021 | 28.74082 | 29.93093 | 21.61646 | 1.38464 | 0.34691 |
| -259 | 0.00026 | 128733.33333 | 184.70641 | 120.82756 | 27.99771 | 28.74332 | 29.95973 | 21.64526 | 1.38412 | 0.34350 |
| -258 | 0.00026 | 128733.33333 | 186.60905 | 122.07812 | 28.02195 | 28.74560 | 29.98514 | 21.67067 | 1.38367 | 0.34114 |
| -257 | 0.00026 | 128733.33333 | 188.49733 | 123.31436 | 28.04596 | 28.74793 | 30.01032 | 21.69585 | 1.38323 | 0.33857 |
| -256 | 0.00027 | 128733.33333 | 190.36406 | 124.53181 | 28.06965 | 28.75030 | 30.03519 | 21.72072 | 1.38279 | 0.33471 |
| -255 | 0.00027 | 128900.00000 | 192.46530 | 125.89673 | 28.09624 | 28.75303 | 30.06314 | 21.74867 | 1.38230 | 0.33235 |
| -254 | 0.00027 | 129066.66667 | 194.54973 | 127.24513 | 28.12257 | 28.75582 | 30.09083 | 21.77636 | 1.38181 | 0.32891 |
| -253 | 0.00027 | 129200.00000 | 196.57377 | 128.54922 | 28.14806 | 28.75860 | 30.11768 | 21.80321 | 1.38134 | 0.32671 |
| -252 | 0.00028 | 129366.66667 | 198.63112 | 129.86956 | 28.17392 | 28.76150 | 30.14494 | 21.83047 | 1.38087 | 0.32321 |
| -251 | 0.00028 | 129533.33333 | 200.67867 | 131.17851 | 28.19960 | 28.76446 | 30.17205 | 21.85757 | 1.38039 | 0.32104 |
| -250 | 0.00028 | 129700.00000 | 202.70913 | 132.47159 | 28.22500 | 28.76747 | 30.19889 | 21.88442 | 1.37993 | 0.31756 |
| -249 | 0.00028 | 129833.33333 | 204.66986 | 133.71566 | 28.24947 | 28.77044 | 30.22478 | 21.91031 | 1.37948 | 0.31404 |
| -248 | 0.00029 | 129833.33333 | 206.40048 | 134.81004 | 28.27103 | 28.77312 | 30.24762 | 21.93315 | 1.37908 | 0.31030 |
| -247 | 0.00029 | 130000.00000 | 208.37654 | 136.05544 | 28.29559 | 28.77623 | 30.27367 | 21.95919 | 1.37863 | 0.30660 |
| -246 | 0.00029 | 130166.66667 | 210.34245 | 137.29010 | 28.31997 | 28.77940 | 30.29956 | 21.98508 | 1.37819 | 0.30440 |
| -245 | 0.00029 | 130333.33333 | 212.28365 | 138.50503 | 28.34398 | 28.78259 | 30.32509 | 22.01062 | 1.37775 | 0.29958 |
| -244 | 0.00029 | 130333.33333 | 213.94098 | 139.53904 | 28.36445 | 28.78537 | 30.34688 | 22.03241 | 1.37737 | 0.29716 |
| -243 | 0.00030 | 130333.33333 | 215.56923 | 140.55203 | 28.38451 | 28.78814 | 30.36827 | 22.05380 | 1.37701 | 0.29195 |
| -242 | 0.00030 | 130333.33333 | 217.18295 | 141.55317 | 28.40437 | 28.79093 | 30.38945 | 22.07498 | 1.37665 | 0.28934 |
| -241 | 0.00030 | 130333.33333 | 218.76759 | 142.53360 | 28.42382 | 28.79371 | 30.41024 | 22.09576 | 1.37629 | 0.28413 |
| -240 | 0.00030 | 130333.33333 | 220.33769 | 143.50245 | 28.44307 | 28.79651 | 30.43082 | 22.11634 | 1.37594 | 0.28152 |
| -239 | 0.00031 | 130333.33333 | 221.87872 | 144.45087 | 28.46192 | 28.79929 | 30.45100 | 22.13653 | 1.37560 | 0.27631 |
| -238 | 0.00031 | 130333.33333 | 223.39794 | 145.38349 | 28.48047 | 28.80207 | 30.47089 | 22.15642 | 1.37526 | 0.27240 |
| -237 | 0.00031 | 130333.33333 | 224.89535 | 146.30042 | 28.49873 | 28.80485 | 30.49048 | 22.17601 | 1.37493 | 0.26849 |
| -236 | 0.00031 | 130333.33333 | 226.37095 | 147.20180 | 28.51669 | 28.80763 | 30.50977 | 22.19530 | 1.37461 | 0.26458 |
| -235 | 0.00031 | 130333.33333 | 227.81748 | 148.08330 | 28.53427 | 28.81038 | 30.52867 | 22.21420 | 1.37429 | 0.25936 |
| -234 | 0.00032 | 130366.66667 | 229.30811 | 148.98951 | 28.55235 | 28.81325 | 30.54814 | 22.23367 | 1.37396 | 0.25679 |
| -233 | 0.00032 | 130333.33333 | 230.65239 | 149.80488 | 28.56863 | 28.81587 | 30.56569 | 22.25122 | 1.37366 | 0.25158 |
| -232 | 0.00032 | 130666.66667 | 232.61965 | 150.99494 | 28.59240 | 28.81976 | 30.59135 | 22.27688 | 1.37323 | 0.24664 |
| -231 | 0.00032 | 130666.66667 | 233.98242 | 151.81714 | 28.60884 | 28.82249 | 30.60911 | 22.29464 | 1.37294 | 0.24435 |
| -230 | 0.00032 | 130833.33333 | 235.61620 | 152.80050 | 28.62852 | 28.82580 | 30.63040 | 22.31593 | 1.37258 | 0.23927 |
| -229 | 0.00032 | 130833.33333 | 236.92964 | 153.58921 | 28.64431 | 28.82849 | 30.64750 | 22.33303 | 1.37229 | 0.23550 |
| -228 | 0.00033 | 130833.33333 | 238.21389 | 154.35882 | 28.65973 | 28.83115 | 30.66422 | 22.34975 | 1.37202 | 0.23027 |
| -227 | 0.00033 | 130833.33333 | 239.47625 | 155.11380 | 28.67486 | 28.83379 | 30.68064 | 22.36617 | 1.37174 | 0.22634 |
| -226 | 0.00033 | 130833.33333 | 240.71672 | 155.85424 | 28.68971 | 28.83641 | 30.69677 | 22.38230 | 1.37148 | 0.22242 |
| -225 | 0.00033 | 131333.33333 | 242.85257 | 157.12581 | 28.71523 | 28.84097 | 30.72453 | 22.41006 | 1.37102 | 0.21760 |
| -224 | 0.00033 | 131333.33333 | 244.04650 | 157.83479 | 28.72946 | 28.84355 | 30.74004 | 22.42556 | 1.37076 | 0.21407 |
| -223 | 0.00033 | 131466.66667 | 245.46742 | 158.67685 | 28.74638 | 28.84665 | 30.75848 | 22.44401 | 1.37045 | 0.21024 |
| -222 | 0.00034 | 131633.33333 | 246.92388 | 159.53809 | 28.76369 | 28.84985 | 30.77738 | 22.46291 | 1.37014 | 0.20522 |
| -221 | 0.00034 | 131933.33333 | 248.61244 | 160.53417 | 28.78372 | 28.85361 | 30.79928 | 22.48481 | 1.36978 | 0.20163 |
| -220 | 0.00034 | 132066.66667 | 249.96118 | 161.32796 | 28.79970 | 28.85665 | 30.81677 | 22.50229 | 1.36949 | 0.19668 |
| -219 | 0.00034 | 132400.00000 | 251.67018 | 162.33146 | 28.81990 | 28.86053 | 30.83891 | 22.52444 | 1.36913 | 0.19306 |
| -218 | 0.00034 | 132733.33333 | 253.35499 | 163.31823 | 28.83978 | 28.86441 | 30.86073 | 22.54625 | 1.36877 | 0.18824 |
| -217 | 0.00034 | 133233.33333 | 255.34224 | 164.47894 | 28.86318 | 28.86903 | 30.88644 | 22.57197 | 1.36835 | 0.18485 |
| -216 | 0.00034 | 133366.66667 | 256.60193 | 165.21291 | 28.87799 | 28.87199 | 30.90274 | 22.58826 | 1.36809 | 0.17996 |
| -215 | 0.00035 | 133866.66667 | 258.54946 | 166.34496 | 28.90083 | 28.87661 | 30.92791 | 22.61344 | 1.36768 | 0.17637 |
| -214 | 0.00035 | 134033.33333 | 259.83568 | 167.09082 | 28.91589 | 28.87970 | 30.94453 | 22.63006 | 1.36741 | 0.17280 |

|      |         |              |           |           |          |          |          |          |         |          |
|------|---------|--------------|-----------|-----------|----------|----------|----------|----------|---------|----------|
| -213 | 0.00035 | 134200.00000 | 261.09436 | 167.81934 | 28.93061 | 28.88274 | 30.96079 | 22.64632 | 1.36714 | 0.16765  |
| -212 | 0.00035 | 134533.33333 | 262.65828 | 168.72264 | 28.94886 | 28.88655 | 30.98098 | 22.66651 | 1.36682 | 0.16393  |
| -211 | 0.00035 | 134533.33333 | 263.54366 | 169.23311 | 28.95918 | 28.88873 | 30.99241 | 22.67793 | 1.36663 | 0.15875  |
| -210 | 0.00035 | 134533.33333 | 264.39903 | 169.72565 | 28.96914 | 28.89084 | 31.00344 | 22.68897 | 1.36645 | 0.15337  |
| -209 | 0.00035 | 134700.00000 | 265.56047 | 170.39345 | 28.98265 | 28.89372 | 31.01842 | 22.70395 | 1.36621 | 0.14942  |
| -208 | 0.00035 | 134700.00000 | 266.37182 | 170.85928 | 28.99208 | 28.89575 | 31.02888 | 22.71441 | 1.36604 | 0.14548  |
| -207 | 0.00036 | 134700.00000 | 267.15312 | 171.30734 | 29.00115 | 28.89771 | 31.03895 | 22.72448 | 1.36588 | 0.14009  |
| -206 | 0.00036 | 134700.00000 | 267.91189 | 171.74199 | 29.00995 | 28.89962 | 31.04873 | 22.73426 | 1.36572 | 0.13605  |
| -205 | 0.00036 | 134700.00000 | 268.64061 | 172.15897 | 29.01839 | 28.90146 | 31.05812 | 22.74365 | 1.36557 | 0.13066  |
| -204 | 0.00036 | 134533.33333 | 269.01352 | 172.37219 | 29.02271 | 28.90241 | 31.06293 | 22.74845 | 1.36550 | 0.12654  |
| -203 | 0.00036 | 134533.33333 | 269.68881 | 172.75800 | 29.03052 | 28.90413 | 31.07162 | 22.75715 | 1.36536 | 0.12108  |
| -202 | 0.00036 | 134366.66667 | 270.00668 | 172.93948 | 29.03420 | 28.90494 | 31.07572 | 22.76125 | 1.36529 | 0.11697  |
| -201 | 0.00036 | 134200.00000 | 270.29299 | 173.10286 | 29.03751 | 28.90567 | 31.07940 | 22.76493 | 1.36523 | 0.11146  |
| -200 | 0.00036 | 133866.66667 | 270.21144 | 173.05633 | 29.03657 | 28.90546 | 31.07835 | 22.76388 | 1.36525 | 0.10589  |
| -199 | 0.00036 | 133533.33333 | 270.10461 | 172.99537 | 29.03533 | 28.90519 | 31.07698 | 22.76251 | 1.36527 | 0.10161  |
| -198 | 0.00036 | 133533.33333 | 270.64827 | 173.30552 | 29.04161 | 28.90658 | 31.08398 | 22.76951 | 1.36516 | 0.09748  |
| -197 | 0.00036 | 133366.66667 | 270.82370 | 173.40555 | 29.04364 | 28.90703 | 31.08624 | 22.77177 | 1.36512 | 0.09208  |
| -196 | 0.00036 | 133366.66667 | 271.31462 | 173.68532 | 29.04931 | 28.90829 | 31.09256 | 22.77809 | 1.36502 | 0.08802  |
| -195 | 0.00037 | 132900.00000 | 270.82481 | 173.40618 | 29.04365 | 28.90703 | 31.08625 | 22.77178 | 1.36512 | 0.08254  |
| -194 | 0.00037 | 132900.00000 | 271.26213 | 173.65542 | 29.04871 | 28.90816 | 31.09188 | 22.77741 | 1.36503 | 0.07841  |
| -193 | 0.00037 | 132733.33333 | 271.32910 | 173.69357 | 29.04948 | 28.90833 | 31.09274 | 22.77827 | 1.36502 | 0.07305  |
| -192 | 0.00037 | 132733.33333 | 271.70665 | 173.90860 | 29.05384 | 28.90930 | 31.09760 | 22.78313 | 1.36494 | 0.06769  |
| -191 | 0.00037 | 132733.33333 | 272.06198 | 174.11087 | 29.05794 | 28.91022 | 31.10218 | 22.78770 | 1.36487 | 0.06371  |
| -190 | 0.00037 | 132733.33333 | 272.39511 | 174.30040 | 29.06178 | 28.91108 | 31.10646 | 22.79199 | 1.36480 | 0.05973  |
| -189 | 0.00037 | 132733.33333 | 272.69863 | 174.47301 | 29.06528 | 28.91187 | 31.11037 | 22.79590 | 1.36474 | 0.05442  |
| -188 | 0.00037 | 132566.66667 | 272.62977 | 174.43386 | 29.06448 | 28.91169 | 31.10948 | 22.79501 | 1.36475 | 0.04908  |
| -187 | 0.00037 | 132566.66667 | 272.88116 | 174.57678 | 29.06738 | 28.91234 | 31.11272 | 22.79825 | 1.36470 | 0.04507  |
| -186 | 0.00037 | 132400.00000 | 272.75961 | 174.50768 | 29.06598 | 28.91203 | 31.11115 | 22.79668 | 1.36472 | 0.03975  |
| -185 | 0.00037 | 132400.00000 | 272.95898 | 174.62101 | 29.06828 | 28.91254 | 31.11372 | 22.79925 | 1.36468 | 0.03575  |
| -184 | 0.00037 | 132400.00000 | 273.13621 | 174.72173 | 29.07032 | 28.91300 | 31.11600 | 22.80153 | 1.36465 | 0.03178  |
| -183 | 0.00037 | 132100.00000 | 272.65730 | 174.44951 | 29.06480 | 28.91176 | 31.10984 | 22.79537 | 1.36474 | 0.02513  |
| -182 | 0.00037 | 132100.00000 | 272.78255 | 174.52072 | 29.06625 | 28.91208 | 31.11145 | 22.79698 | 1.36472 | 0.02246  |
| -181 | 0.00037 | 132100.00000 | 272.87096 | 174.57098 | 29.06726 | 28.91231 | 31.11259 | 22.79811 | 1.36470 | 0.01585  |
| -180 | 0.00037 | 132100.00000 | 272.93727 | 174.60867 | 29.06803 | 28.91249 | 31.11344 | 22.79897 | 1.36469 | 0.01189  |
| -179 | 0.00037 | 132266.66667 | 273.32588 | 174.82949 | 29.07251 | 28.91350 | 31.11844 | 22.80397 | 1.36461 | 0.00793  |
| -178 | 0.00037 | 132266.66667 | 273.34064 | 174.83787 | 29.07268 | 28.91353 | 31.11863 | 22.80416 | 1.36460 | 0.00265  |
| -177 | 0.00037 | 132433.33333 | 273.67030 | 175.02509 | 29.07647 | 28.91439 | 31.12287 | 22.80840 | 1.36454 | -0.00265 |
| -176 | 0.00037 | 132433.33333 | 273.63337 | 175.00412 | 29.07605 | 28.91430 | 31.12239 | 22.80792 | 1.36454 | -0.00662 |
| -175 | 0.00037 | 132266.66667 | 273.22998 | 174.77501 | 29.07140 | 28.91325 | 31.11721 | 22.80273 | 1.36463 | -0.01059 |
| -174 | 0.00037 | 132433.33333 | 273.47826 | 174.91604 | 29.07426 | 28.91389 | 31.12040 | 22.80593 | 1.36458 | -0.01721 |
| -173 | 0.00037 | 132433.33333 | 273.36747 | 174.85311 | 29.07298 | 28.91360 | 31.11897 | 22.80450 | 1.36460 | -0.01986 |
| -172 | 0.00037 | 132433.33333 | 273.21974 | 174.76919 | 29.07128 | 28.91322 | 31.11707 | 22.80260 | 1.36463 | -0.02649 |
| -171 | 0.00037 | 132433.33333 | 273.04986 | 174.67266 | 29.06933 | 28.91278 | 31.11489 | 22.80042 | 1.36466 | -0.03046 |
| -170 | 0.00037 | 132433.33333 | 272.85044 | 174.55932 | 29.06703 | 28.91226 | 31.11232 | 22.79785 | 1.36470 | -0.03576 |
| -169 | 0.00037 | 132600.00000 | 272.97196 | 174.62839 | 29.06843 | 28.91258 | 31.11389 | 22.79941 | 1.36468 | -0.03976 |
| -168 | 0.00037 | 132766.66667 | 273.06330 | 174.68030 | 29.06948 | 28.91281 | 31.11506 | 22.80059 | 1.36466 | -0.04511 |
| -167 | 0.00037 | 132933.33333 | 273.13177 | 174.71920 | 29.07027 | 28.91299 | 31.11594 | 22.80147 | 1.36465 | -0.04915 |
| -166 | 0.00037 | 133066.66667 | 273.10144 | 174.70197 | 29.06992 | 28.91291 | 31.11555 | 22.80108 | 1.36465 | -0.05453 |
| -165 | 0.00037 | 133233.33333 | 273.10912 | 174.70634 | 29.07001 | 28.91293 | 31.11565 | 22.80118 | 1.36465 | -0.05992 |
| -164 | 0.00037 | 133533.33333 | 273.36660 | 174.85262 | 29.07297 | 28.91360 | 31.11896 | 22.80449 | 1.36460 | -0.06402 |
| -163 | 0.00037 | 133533.33333 | 272.97933 | 174.63258 | 29.06851 | 28.91260 | 31.11398 | 22.79951 | 1.36468 | -0.06944 |
| -162 | 0.00037 | 133866.66667 | 273.24266 | 174.78221 | 29.07155 | 28.91328 | 31.11737 | 22.80290 | 1.36462 | -0.07487 |

|      |         |              |           |           |          |          |          |          |         |          |
|------|---------|--------------|-----------|-----------|----------|----------|----------|----------|---------|----------|
| -161 | 0.00037 | 134166.66667 | 273.41352 | 174.87927 | 29.07352 | 28.91372 | 31.11957 | 22.80509 | 1.36459 | -0.07907 |
| -160 | 0.00036 | 134666.66667 | 273.95928 | 175.18913 | 29.07980 | 28.91515 | 31.12659 | 22.81211 | 1.36448 | -0.08468 |
| -159 | 0.00036 | 134666.66667 | 273.45606 | 174.90343 | 29.07401 | 28.91384 | 31.12011 | 22.80564 | 1.36458 | -0.09023 |
| -158 | 0.00036 | 135133.33333 | 273.87611 | 175.14193 | 29.07884 | 28.91493 | 31.12552 | 22.81104 | 1.36449 | -0.09443 |
| -157 | 0.00036 | 135633.33333 | 274.32969 | 175.39930 | 29.08406 | 28.91612 | 31.13135 | 22.81688 | 1.36440 | -0.10018 |
| -156 | 0.00036 | 135966.66667 | 274.41240 | 175.44621 | 29.08501 | 28.91633 | 31.13241 | 22.81794 | 1.36438 | -0.10592 |
| -155 | 0.00036 | 136266.66667 | 274.40227 | 175.44047 | 29.08490 | 28.91631 | 31.13228 | 22.81781 | 1.36439 | -0.11025 |
| -154 | 0.00036 | 136733.33333 | 274.69380 | 175.60578 | 29.08825 | 28.91707 | 31.13603 | 22.82156 | 1.36433 | -0.11602 |
| -153 | 0.00036 | 137066.66667 | 274.68310 | 175.59971 | 29.08813 | 28.91704 | 31.13590 | 22.82142 | 1.36433 | -0.12184 |
| -152 | 0.00036 | 137700.00000 | 275.24576 | 175.91858 | 29.09460 | 28.91852 | 31.14313 | 22.82866 | 1.36421 | -0.12639 |
| -151 | 0.00036 | 138200.00000 | 275.50526 | 176.06556 | 29.09758 | 28.91920 | 31.14647 | 22.83199 | 1.36416 | -0.13243 |
| -150 | 0.00036 | 138833.33333 | 275.99352 | 176.34195 | 29.10319 | 28.92049 | 31.15274 | 22.83827 | 1.36406 | -0.13852 |
| -149 | 0.00036 | 139466.66667 | 276.44360 | 176.59657 | 29.10835 | 28.92168 | 31.15853 | 22.84406 | 1.36397 | -0.14472 |
| -148 | 0.00035 | 140300.00000 | 277.25813 | 177.05693 | 29.11770 | 28.92384 | 31.16900 | 22.85452 | 1.36380 | -0.14968 |
| -147 | 0.00035 | 140933.33333 | 277.63723 | 177.27101 | 29.12204 | 28.92485 | 31.17387 | 22.85939 | 1.36372 | -0.15608 |
| -146 | 0.00035 | 141533.33333 | 277.91146 | 177.42580 | 29.12519 | 28.92558 | 31.17739 | 22.86292 | 1.36367 | -0.16242 |
| -145 | 0.00035 | 142366.66667 | 278.61084 | 177.82028 | 29.13320 | 28.92744 | 31.18637 | 22.87190 | 1.36352 | -0.16750 |
| -144 | 0.00035 | 143000.00000 | 278.87726 | 177.97046 | 29.13625 | 28.92816 | 31.18979 | 22.87532 | 1.36347 | -0.17407 |
| -143 | 0.00035 | 143666.66667 | 279.16780 | 178.13415 | 29.13957 | 28.92894 | 31.19353 | 22.87905 | 1.36341 | -0.18060 |
| -142 | 0.00035 | 144600.00000 | 279.93301 | 178.56498 | 29.14832 | 28.93100 | 31.20335 | 22.88888 | 1.36325 | -0.18737 |
| -141 | 0.00035 | 145066.66667 | 279.76037 | 178.46782 | 29.14635 | 28.93053 | 31.20113 | 22.88666 | 1.36329 | -0.19263 |
| -140 | 0.00034 | 146066.66667 | 280.57280 | 178.92483 | 29.15563 | 28.93272 | 31.21156 | 22.89709 | 1.36312 | -0.19943 |
| -139 | 0.00034 | 146833.33333 | 280.89077 | 179.10355 | 29.15926 | 28.93358 | 31.21565 | 22.90117 | 1.36306 | -0.20649 |
| -138 | 0.00034 | 147800.00000 | 281.54474 | 179.47087 | 29.16673 | 28.93536 | 31.22404 | 22.90957 | 1.36293 | -0.21361 |
| -137 | 0.00034 | 148633.33333 | 281.90530 | 179.67325 | 29.17084 | 28.93634 | 31.22867 | 22.91419 | 1.36285 | -0.21936 |
| -136 | 0.00034 | 149566.66667 | 282.40757 | 179.95498 | 29.17657 | 28.93771 | 31.23511 | 22.92064 | 1.36275 | -0.22663 |
| -135 | 0.00034 | 150533.33333 | 282.92309 | 180.24395 | 29.18244 | 28.93911 | 31.24172 | 22.92725 | 1.36265 | -0.23408 |
| -134 | 0.00034 | 151533.33333 | 283.45034 | 180.53927 | 29.18845 | 28.94056 | 31.24849 | 22.93401 | 1.36254 | -0.24165 |
| -133 | 0.00033 | 152600.00000 | 284.05832 | 180.87953 | 29.19537 | 28.94223 | 31.25628 | 22.94181 | 1.36242 | -0.24787 |
| -132 | 0.00033 | 153600.00000 | 284.48915 | 181.12048 | 29.20027 | 28.94342 | 31.26181 | 22.94733 | 1.36233 | -0.25568 |
| -131 | 0.00033 | 154366.66667 | 284.43692 | 181.09127 | 29.19967 | 28.94327 | 31.26114 | 22.94666 | 1.36234 | -0.26331 |
| -130 | 0.00033 | 155666.66667 | 285.32166 | 181.58564 | 29.20973 | 28.94572 | 31.27248 | 22.95801 | 1.36216 | -0.26973 |
| -129 | 0.00033 | 156800.00000 | 285.84232 | 181.87628 | 29.21564 | 28.94716 | 31.27915 | 22.96468 | 1.36205 | -0.27810 |
| -128 | 0.00033 | 157900.00000 | 286.24482 | 182.10082 | 29.22021 | 28.94828 | 31.28431 | 22.96984 | 1.36197 | -0.28638 |
| -127 | 0.00032 | 159233.33333 | 287.01897 | 182.53232 | 29.22899 | 28.95043 | 31.29423 | 22.97976 | 1.36182 | -0.29335 |
| -126 | 0.00032 | 160633.33333 | 287.84924 | 182.99458 | 29.23840 | 28.95276 | 31.30487 | 22.99039 | 1.36165 | -0.30227 |
| -125 | 0.00032 | 161900.00000 | 288.38539 | 183.29280 | 29.24447 | 28.95426 | 31.31173 | 22.99726 | 1.36154 | -0.30963 |
| -124 | 0.00032 | 163200.00000 | 288.91703 | 183.58829 | 29.25049 | 28.95576 | 31.31854 | 23.00407 | 1.36143 | -0.31860 |
| -123 | 0.00032 | 164633.33333 | 289.61810 | 183.97761 | 29.25841 | 28.95774 | 31.32751 | 23.01304 | 1.36129 | -0.32783 |
| -122 | 0.00031 | 166100.00000 | 290.31767 | 184.36571 | 29.26632 | 28.95972 | 31.33647 | 23.02200 | 1.36115 | -0.33569 |
| -121 | 0.00031 | 167533.33333 | 290.88877 | 184.68226 | 29.27277 | 28.96134 | 31.34378 | 23.02931 | 1.36104 | -0.34531 |
| -120 | 0.00031 | 169166.66667 | 291.73398 | 185.15029 | 29.28230 | 28.96375 | 31.35459 | 23.04012 | 1.36087 | -0.35522 |
| -119 | 0.00031 | 170733.33333 | 292.40753 | 185.52285 | 29.28989 | 28.96568 | 31.36321 | 23.04874 | 1.36073 | -0.36199 |
| -118 | 0.00030 | 172166.66667 | 292.76907 | 185.72269 | 29.29397 | 28.96671 | 31.36783 | 23.05336 | 1.36066 | -0.37376 |
| -117 | 0.00030 | 173966.66667 | 293.69541 | 186.23426 | 29.30439 | 28.96938 | 31.37968 | 23.06521 | 1.36048 | -0.38075 |
| -116 | 0.00030 | 175566.66667 | 294.20322 | 186.51441 | 29.31010 | 28.97084 | 31.38617 | 23.07170 | 1.36038 | -0.39148 |
| -115 | 0.00030 | 177300.00000 | 294.85327 | 186.87274 | 29.31741 | 28.97272 | 31.39448 | 23.08001 | 1.36025 | -0.40227 |
| -114 | 0.00030 | 179233.33333 | 295.75930 | 187.37165 | 29.32758 | 28.97535 | 31.40606 | 23.09159 | 1.36006 | -0.41180 |
| -113 | 0.00029 | 181166.66667 | 296.58521 | 187.82588 | 29.33685 | 28.97776 | 31.41661 | 23.10214 | 1.35990 | -0.42167 |
| -112 | 0.00029 | 183233.33333 | 297.54653 | 188.35392 | 29.34762 | 28.98057 | 31.42889 | 23.11442 | 1.35971 | -0.43181 |
| -111 | 0.00029 | 185333.33333 | 298.47590 | 188.86375 | 29.35802 | 28.98330 | 31.44076 | 23.12629 | 1.35952 | -0.44228 |
| -110 | 0.00029 | 187566.66667 | 299.52015 | 189.43581 | 29.36970 | 28.98639 | 31.45409 | 23.13962 | 1.35932 | -0.45494 |

|      |         |              |           |           |          |          |          |          |         |          |
|------|---------|--------------|-----------|-----------|----------|----------|----------|----------|---------|----------|
| -109 | 0.00028 | 189966.66667 | 300.73571 | 190.10066 | 29.38327 | 28.98999 | 31.46960 | 23.15513 | 1.35908 | -0.46625 |
| -108 | 0.00028 | 192200.00000 | 301.59143 | 190.56803 | 29.39282 | 28.99254 | 31.48052 | 23.16604 | 1.35891 | -0.47771 |
| -107 | 0.00028 | 194466.66667 | 302.40418 | 191.01142 | 29.40187 | 28.99497 | 31.49088 | 23.17641 | 1.35875 | -0.48913 |
| -106 | 0.00028 | 197200.00000 | 303.85007 | 191.79897 | 29.41796 | 28.99932 | 31.50932 | 23.19485 | 1.35846 | -0.49938 |
| -105 | 0.00027 | 199933.33333 | 305.17360 | 192.51850 | 29.43266 | 29.00332 | 31.52619 | 23.21171 | 1.35820 | -0.51429 |
| -104 | 0.00027 | 202500.00000 | 306.13230 | 193.03886 | 29.44330 | 29.00624 | 31.53840 | 23.22393 | 1.35801 | -0.52719 |
| -103 | 0.00027 | 205233.33333 | 307.24263 | 193.64066 | 29.45560 | 29.00962 | 31.55254 | 23.23807 | 1.35780 | -0.53821 |
| -102 | 0.00027 | 208100.00000 | 308.43528 | 194.28606 | 29.46880 | 29.01328 | 31.56772 | 23.25325 | 1.35756 | -0.55180 |
| -101 | 0.00026 | 211133.33333 | 309.75178 | 194.99725 | 29.48335 | 29.01734 | 31.58448 | 23.27001 | 1.35730 | -0.56596 |
| -100 | 0.00026 | 214533.33333 | 311.48540 | 195.93180 | 29.50247 | 29.02272 | 31.60653 | 23.29206 | 1.35697 | -0.57891 |
| -99  | 0.00026 | 217733.33333 | 312.79209 | 196.63473 | 29.51686 | 29.02679 | 31.62315 | 23.30868 | 1.35671 | -0.59437 |
| -98  | 0.00025 | 221100.00000 | 314.21282 | 197.39758 | 29.53248 | 29.03125 | 31.64120 | 23.32673 | 1.35644 | -0.60778 |
| -97  | 0.00025 | 224300.00000 | 315.25773 | 197.95768 | 29.54395 | 29.03455 | 31.65448 | 23.34001 | 1.35623 | -0.62356 |
| -96  | 0.00025 | 227800.00000 | 316.59425 | 198.67293 | 29.55860 | 29.03878 | 31.67145 | 23.35698 | 1.35597 | -0.63746 |
| -95  | 0.00025 | 231533.33333 | 318.11547 | 199.48542 | 29.57525 | 29.04363 | 31.69077 | 23.37629 | 1.35568 | -0.65225 |
| -94  | 0.00024 | 235200.00000 | 319.38852 | 200.16407 | 29.58916 | 29.04771 | 31.70692 | 23.39245 | 1.35543 | -0.66976 |
| -93  | 0.00024 | 239233.33333 | 321.02290 | 201.03359 | 29.60699 | 29.05297 | 31.72765 | 23.41318 | 1.35512 | -0.68318 |
| -92  | 0.00024 | 243200.00000 | 322.41219 | 201.77120 | 29.62212 | 29.05747 | 31.74526 | 23.43079 | 1.35485 | -0.69953 |
| -91  | 0.00023 | 247400.00000 | 323.93733 | 202.57933 | 29.63870 | 29.06244 | 31.76459 | 23.45012 | 1.35456 | -0.71873 |
| -90  | 0.00023 | 251566.66667 | 325.26807 | 203.28307 | 29.65314 | 29.06680 | 31.78145 | 23.46698 | 1.35431 | -0.73348 |
| -89  | 0.00023 | 255900.00000 | 326.66065 | 204.01816 | 29.66823 | 29.07139 | 31.79908 | 23.48461 | 1.35404 | -0.74851 |
| -88  | 0.00023 | 260366.66667 | 328.03510 | 204.74230 | 29.68310 | 29.07593 | 31.81647 | 23.50200 | 1.35378 | -0.76924 |
| -87  | 0.00022 | 264866.66667 | 329.28773 | 205.40108 | 29.69663 | 29.08010 | 31.83232 | 23.51785 | 1.35354 | -0.78522 |
| -86  | 0.00022 | 269666.66667 | 330.74321 | 206.16513 | 29.71232 | 29.08496 | 31.85073 | 23.53625 | 1.35326 | -0.80180 |
| -85  | 0.00022 | 274633.33333 | 332.22438 | 206.94112 | 29.72827 | 29.08993 | 31.86945 | 23.55498 | 1.35298 | -0.81917 |
| -84  | 0.00021 | 279633.33333 | 333.54736 | 207.63291 | 29.74249 | 29.09440 | 31.88616 | 23.57169 | 1.35273 | -0.83971 |
| -83  | 0.00021 | 284766.66667 | 334.84225 | 208.30881 | 29.75639 | 29.09879 | 31.90251 | 23.58804 | 1.35249 | -0.85789 |
| -82  | 0.00021 | 289900.00000 | 335.94691 | 208.88447 | 29.76822 | 29.10255 | 31.91646 | 23.60199 | 1.35228 | -0.87637 |
| -81  | 0.00020 | 295333.33333 | 337.20301 | 209.53800 | 29.78167 | 29.10684 | 31.93231 | 23.61784 | 1.35204 | -0.89541 |
| -80  | 0.00020 | 301100.00000 | 338.64855 | 210.28872 | 29.79711 | 29.11180 | 31.95054 | 23.63607 | 1.35177 | -0.91254 |
| -79  | 0.00020 | 307033.33333 | 340.06474 | 211.02277 | 29.81222 | 29.11669 | 31.96840 | 23.65393 | 1.35150 | -0.93348 |
| -78  | 0.00020 | 313133.33333 | 341.44203 | 211.73530 | 29.82689 | 29.12146 | 31.98576 | 23.67129 | 1.35125 | -0.95506 |
| -77  | 0.00019 | 319566.66667 | 342.96749 | 212.52294 | 29.84310 | 29.12678 | 32.00497 | 23.69050 | 1.35096 | -0.97436 |
| -76  | 0.00019 | 326300.00000 | 344.57054 | 213.34890 | 29.86012 | 29.13239 | 32.02516 | 23.71068 | 1.35066 | -0.99786 |
| -75  | 0.00019 | 333366.66667 | 346.30636 | 214.24124 | 29.87850 | 29.13850 | 32.04700 | 23.73253 | 1.35034 | -1.01589 |
| -74  | 0.00018 | 340733.33333 | 348.08689 | 215.15438 | 29.89732 | 29.14480 | 32.06939 | 23.75492 | 1.35001 | -1.04148 |
| -73  | 0.00018 | 348100.00000 | 349.61351 | 215.93556 | 29.91343 | 29.15024 | 32.08858 | 23.77411 | 1.34973 | -1.06425 |
| -72  | 0.00018 | 355633.33333 | 351.07057 | 216.67965 | 29.92877 | 29.15545 | 32.10688 | 23.79241 | 1.34946 | -1.08375 |
| -71  | 0.00017 | 363633.33333 | 352.72148 | 217.52096 | 29.94612 | 29.16138 | 32.12762 | 23.81314 | 1.34915 | -1.10767 |
| -70  | 0.00017 | 372000.00000 | 354.44691 | 218.39824 | 29.96423 | 29.16761 | 32.14927 | 23.83480 | 1.34884 | -1.13288 |
| -69  | 0.00017 | 380933.33333 | 356.43634 | 219.40721 | 29.98505 | 29.17483 | 32.17422 | 23.85975 | 1.34847 | -1.15575 |
| -68  | 0.00016 | 390400.00000 | 358.60976 | 220.50641 | 30.00775 | 29.18278 | 32.20146 | 23.88699 | 1.34808 | -1.18400 |
| -67  | 0.00016 | 400333.33333 | 360.90200 | 221.66221 | 30.03162 | 29.19121 | 32.23017 | 23.91570 | 1.34766 | -1.20982 |
| -66  | 0.00016 | 410266.66667 | 362.90096 | 222.66721 | 30.05239 | 29.19861 | 32.25519 | 23.94071 | 1.34729 | -1.23211 |
| -65  | 0.00016 | 420700.00000 | 364.99687 | 223.71806 | 30.07411 | 29.20642 | 32.28140 | 23.96693 | 1.34691 | -1.26307 |
| -64  | 0.00015 | 431633.33333 | 367.18839 | 224.81367 | 30.09677 | 29.21463 | 32.30879 | 23.99432 | 1.34652 | -1.29129 |
| -63  | 0.00015 | 443500.00000 | 369.83807 | 226.13401 | 30.12409 | 29.22463 | 32.34187 | 24.02740 | 1.34604 | -1.31708 |
| -62  | 0.00015 | 455666.66667 | 372.35987 | 227.38626 | 30.15001 | 29.23421 | 32.37333 | 24.05886 | 1.34559 | -1.34875 |
| -61  | 0.00014 | 468333.33333 | 374.92699 | 228.65665 | 30.17631 | 29.24403 | 32.40533 | 24.09086 | 1.34513 | -1.37676 |
| -60  | 0.00014 | 481333.33333 | 377.38808 | 229.87045 | 30.20146 | 29.25351 | 32.43598 | 24.12151 | 1.34469 | -1.40551 |
| -59  | 0.00014 | 494966.66667 | 379.93365 | 231.12169 | 30.22739 | 29.26338 | 32.46766 | 24.15318 | 1.34424 | -1.44004 |
| -58  | 0.00013 | 509533.33333 | 382.78851 | 232.51986 | 30.25638 | 29.27453 | 32.50314 | 24.18867 | 1.34373 | -1.47159 |

|     |         |               |           |           |          |          |          |          |         |          |
|-----|---------|---------------|-----------|-----------|----------|----------|----------|----------|---------|----------|
| -57 | 0.00013 | 525266.66667  | 386.11258 | 234.14107 | 30.29001 | 29.28762 | 32.54442 | 24.22995 | 1.34315 | -1.50046 |
| -56 | 0.00013 | 541133.33333  | 389.05374 | 235.56948 | 30.31966 | 29.29929 | 32.58090 | 24.26643 | 1.34263 | -1.54095 |
| -55 | 0.00013 | 557833.33333  | 392.16245 | 237.07313 | 30.35089 | 29.31171 | 32.61941 | 24.30494 | 1.34209 | -1.57152 |
| -54 | 0.00012 | 575300.00000  | 395.36141 | 238.61387 | 30.38291 | 29.32460 | 32.65900 | 24.34453 | 1.34153 | -1.60338 |
| -53 | 0.00012 | 593233.33333  | 398.38850 | 240.06573 | 30.41309 | 29.33688 | 32.69642 | 24.38195 | 1.34101 | -1.64179 |
| -52 | 0.00012 | 611866.66667  | 401.41499 | 241.51139 | 30.44316 | 29.34925 | 32.73378 | 24.41931 | 1.34049 | -1.67509 |
| -51 | 0.00011 | 630766.66667  | 404.14002 | 242.80802 | 30.47015 | 29.36046 | 32.76739 | 24.45292 | 1.34002 | -1.70862 |
| -50 | 0.00011 | 651133.33333  | 407.31146 | 244.31107 | 30.50144 | 29.37359 | 32.80646 | 24.49199 | 1.33948 | -1.74338 |
| -49 | 0.00011 | 672000.00000  | 410.24511 | 245.69571 | 30.53029 | 29.38582 | 32.84256 | 24.52809 | 1.33898 | -1.78623 |
| -48 | 0.00011 | 693333.33333  | 413.02153 | 247.00111 | 30.55750 | 29.39747 | 32.87669 | 24.56222 | 1.33851 | -1.80907 |
| -47 | 0.00010 | 716233.33333  | 416.15736 | 248.46961 | 30.58812 | 29.41071 | 32.91519 | 24.60072 | 1.33798 | -1.85358 |
| -46 | 0.00010 | 739833.33333  | 419.18289 | 249.88059 | 30.61756 | 29.42357 | 32.95229 | 24.63782 | 1.33747 | -1.88561 |
| -45 | 0.00010 | 764500.00000  | 422.28613 | 251.32182 | 30.64764 | 29.43684 | 32.99030 | 24.67582 | 1.33695 | -1.91803 |
| -44 | 0.00010 | 790533.33333  | 425.55549 | 252.83367 | 30.67922 | 29.45091 | 33.03029 | 24.71582 | 1.33640 | -1.95934 |
| -43 | 0.00009 | 817100.00000  | 428.55496 | 254.21486 | 30.70809 | 29.46390 | 33.06693 | 24.75246 | 1.33590 | -1.99347 |
| -42 | 0.00009 | 845300.00000  | 431.84216 | 255.72211 | 30.73960 | 29.47823 | 33.10704 | 24.79256 | 1.33536 | -2.02813 |
| -41 | 0.00009 | 874033.33333  | 434.82204 | 257.08266 | 30.76807 | 29.49130 | 33.14335 | 24.82888 | 1.33487 | -2.06320 |
| -40 | 0.00009 | 905000.00000  | 438.36624 | 258.69374 | 30.80179 | 29.50693 | 33.18648 | 24.87200 | 1.33429 | -2.09036 |
| -39 | 0.00008 | 937200.00000  | 441.88903 | 260.28744 | 30.83517 | 29.52258 | 33.22928 | 24.91481 | 1.33372 | -2.12774 |
| -38 | 0.00008 | 970866.66667  | 445.47136 | 261.90027 | 30.86897 | 29.53859 | 33.27274 | 24.95827 | 1.33313 | -2.16566 |
| -37 | 0.00008 | 1005366.66667 | 448.79732 | 263.39068 | 30.90023 | 29.55355 | 33.31304 | 24.99857 | 1.33260 | -2.20350 |
| -36 | 0.00008 | 1041766.66667 | 452.43827 | 265.01452 | 30.93431 | 29.57002 | 33.35708 | 25.04261 | 1.33201 | -2.22114 |
| -35 | 0.00008 | 1081066.66667 | 456.66368 | 266.88899 | 30.97367 | 29.58927 | 33.40811 | 25.09364 | 1.33134 | -2.26082 |
| -34 | 0.00007 | 1120000.00000 | 460.05470 | 268.38552 | 31.00512 | 29.60481 | 33.44899 | 25.13452 | 1.33080 | -2.30011 |
| -33 | 0.00007 | 1160900.00000 | 463.71146 | 269.99160 | 31.03889 | 29.62168 | 33.49301 | 25.17853 | 1.33022 | -2.31511 |
| -32 | 0.00007 | 1202900.00000 | 467.20446 | 271.51830 | 31.07101 | 29.63787 | 33.53499 | 25.22051 | 1.32967 | -2.34016 |
| -31 | 0.00007 | 1246066.66667 | 470.55760 | 272.97703 | 31.10172 | 29.65351 | 33.57522 | 25.26075 | 1.32915 | -2.36325 |
| -30 | 0.00007 | 1291266.66667 | 474.08749 | 274.50545 | 31.13392 | 29.67006 | 33.61751 | 25.30304 | 1.32860 | -2.38509 |
| -29 | 0.00006 | 1337300.00000 | 477.33966 | 275.90710 | 31.16346 | 29.68538 | 33.65642 | 25.34194 | 1.32809 | -2.40514 |
| -28 | 0.00006 | 1386333.33333 | 481.15629 | 277.54409 | 31.19799 | 29.70346 | 33.70200 | 25.38752 | 1.32750 | -2.41042 |
| -27 | 0.00006 | 1436700.00000 | 484.85507 | 279.12238 | 31.23131 | 29.72107 | 33.74609 | 25.43162 | 1.32693 | -2.42781 |
| -26 | 0.00006 | 1488500.00000 | 488.55561 | 280.69342 | 31.26449 | 29.73879 | 33.79013 | 25.47566 | 1.32637 | -2.42792 |
| -25 | 0.00006 | 1541600.00000 | 492.14154 | 282.20821 | 31.29651 | 29.75605 | 33.83274 | 25.51826 | 1.32582 | -2.43923 |
| -24 | 0.00006 | 1595466.66667 | 495.63461 | 283.67661 | 31.32757 | 29.77294 | 33.87416 | 25.55969 | 1.32530 | -2.41554 |
| -23 | 0.00005 | 1650300.00000 | 498.86253 | 285.02728 | 31.35615 | 29.78862 | 33.91239 | 25.59792 | 1.32481 | -2.43432 |
| -22 | 0.00005 | 1706866.66667 | 502.34882 | 286.47933 | 31.38690 | 29.80563 | 33.95360 | 25.63913 | 1.32429 | -2.40037 |
| -21 | 0.00005 | 1764633.33333 | 505.86694 | 287.93758 | 31.41781 | 29.82287 | 33.99512 | 25.68065 | 1.32376 | -2.37798 |
| -20 | 0.00005 | 1822833.33333 | 509.13151 | 289.28441 | 31.44637 | 29.83894 | 34.03358 | 25.71911 | 1.32328 | -2.36773 |
| -19 | 0.00005 | 1880866.66667 | 512.22814 | 290.55634 | 31.47336 | 29.85424 | 34.07001 | 25.75554 | 1.32282 | -2.31481 |
| -18 | 0.00005 | 1939266.66667 | 515.26184 | 291.79716 | 31.49970 | 29.86929 | 34.10564 | 25.79117 | 1.32238 | -2.27298 |
| -17 | 0.00005 | 1997466.66667 | 518.02556 | 292.92301 | 31.52362 | 29.88304 | 34.13806 | 25.82358 | 1.32197 | -2.24394 |
| -16 | 0.00005 | 2056000.00000 | 521.05088 | 294.15050 | 31.54971 | 29.89815 | 34.17348 | 25.85901 | 1.32153 | -2.14834 |
| -15 | 0.00004 | 2113366.66667 | 523.68467 | 295.21495 | 31.57235 | 29.91135 | 34.20428 | 25.88981 | 1.32115 | -2.10553 |
| -14 | 0.00004 | 2169500.00000 | 526.09950 | 296.18748 | 31.59304 | 29.92348 | 34.23249 | 25.91801 | 1.32080 | -2.03436 |
| -13 | 0.00004 | 2224033.33333 | 528.40825 | 297.11425 | 31.61277 | 29.93512 | 34.25942 | 25.94495 | 1.32047 | -1.93315 |
| -12 | 0.00004 | 2276800.00000 | 530.65951 | 298.01507 | 31.63196 | 29.94649 | 34.28565 | 25.97117 | 1.32014 | -1.82284 |
| -11 | 0.00004 | 2327166.66667 | 532.53444 | 298.76316 | 31.64790 | 29.95598 | 34.30747 | 25.99300 | 1.31987 | -1.74951 |
| -10 | 0.00004 | 2375400.00000 | 534.43063 | 299.51775 | 31.66399 | 29.96560 | 34.32951 | 26.01504 | 1.31960 | -1.62239 |
| -9  | 0.00004 | 2420766.66667 | 536.26675 | 300.24653 | 31.67953 | 29.97493 | 34.35084 | 26.03637 | 1.31934 | -1.48681 |
| -8  | 0.00004 | 2462166.66667 | 537.74803 | 300.83311 | 31.69204 | 29.98247 | 34.36803 | 26.05356 | 1.31913 | -1.36722 |
| -7  | 0.00004 | 2499366.66667 | 539.04229 | 301.34464 | 31.70295 | 29.98907 | 34.38304 | 26.06857 | 1.31895 | -1.21558 |
| -6  | 0.00004 | 2532066.66667 | 540.02233 | 301.73137 | 31.71121 | 29.99408 | 34.39440 | 26.07993 | 1.31881 | -1.08176 |

|    |         |               |            |           |          |          |          |          |         |          |
|----|---------|---------------|------------|-----------|----------|----------|----------|----------|---------|----------|
| -5 | 0.00004 | 2559500.00000 | 540.73415  | 302.01192 | 31.71720 | 29.99772 | 34.40264 | 26.08817 | 1.31871 | -0.91648 |
| -4 | 0.00004 | 2581433.33333 | 541.04874  | 302.13582 | 31.71984 | 29.99932 | 34.40629 | 26.09182 | 1.31866 | -0.77114 |
| -3 | 0.00004 | 2598133.33333 | 541.21614  | 302.20173 | 31.72125 | 30.00018 | 34.40823 | 26.09375 | 1.31864 | -0.59565 |
| -2 | 0.00004 | 2609033.33333 | 541.15852  | 302.17905 | 31.72076 | 29.99989 | 34.40756 | 26.09309 | 1.31865 | -0.41657 |
| -1 | 0.00004 | 2614466.66667 | 540.82734  | 302.04863 | 31.71798 | 29.99819 | 34.40372 | 26.08925 | 1.31869 | -0.26117 |
| 0  | 0.00004 | 2614333.33333 | 540.21653  | 301.80794 | 31.71284 | 29.99507 | 34.39665 | 26.08218 | 1.31878 | -0.10458 |
| 1  | 0.00004 | 2608533.33333 | 539.59997  | 301.56477 | 31.70765 | 29.99192 | 34.38950 | 26.07503 | 1.31887 | 0.10446  |
| 2  | 0.00004 | 2596533.33333 | 538.56581  | 301.15643 | 31.69894 | 29.98664 | 34.37752 | 26.06304 | 1.31901 | 0.26025  |
| 3  | 0.00004 | 2578733.33333 | 537.17493  | 300.60631 | 31.68720 | 29.97956 | 34.36138 | 26.04691 | 1.31921 | 0.41402  |
| 4  | 0.00004 | 2555800.00000 | 535.67618  | 300.01233 | 31.67453 | 29.97193 | 34.34398 | 26.02951 | 1.31942 | 0.59047  |
| 5  | 0.00004 | 2527100.00000 | 533.88915  | 299.30247 | 31.65940 | 29.96285 | 34.32322 | 26.00875 | 1.31968 | 0.76244  |
| 6  | 0.00004 | 2493566.66667 | 531.81130  | 298.47486 | 31.64176 | 29.95232 | 34.29905 | 25.98458 | 1.31998 | 0.90372  |
| 7  | 0.00004 | 2455900.00000 | 529.53080  | 297.56378 | 31.62235 | 29.94078 | 34.27250 | 25.95803 | 1.32030 | 1.03939  |
| 8  | 0.00004 | 2415500.00000 | 527.42111  | 296.71836 | 31.60434 | 29.93014 | 34.24791 | 25.93343 | 1.32061 | 1.19349  |
| 9  | 0.00004 | 2373933.33333 | 525.75947  | 296.05074 | 31.59013 | 29.92177 | 34.22852 | 25.91405 | 1.32085 | 1.34104  |
| 10 | 0.00004 | 2335000.00000 | 525.21099  | 295.83003 | 31.58544 | 29.91901 | 34.22211 | 25.90764 | 1.32093 | 1.45977  |
| 11 | 0.00004 | 2304066.66667 | 526.99137  | 296.54585 | 31.60067 | 29.92797 | 34.24289 | 25.92842 | 1.32067 | 1.57728  |
| 12 | 0.00004 | 2285600.00000 | 532.32813  | 298.68094 | 31.64615 | 29.95493 | 34.30507 | 25.99059 | 1.31990 | 1.72112  |
| 13 | 0.00004 | 2287200.00000 | 543.03333  | 302.91621 | 31.73650 | 30.00948 | 34.42926 | 26.11479 | 1.31838 | 1.85198  |
| 14 | 0.00004 | 2315100.00000 | 560.89074  | 309.84140 | 31.88469 | 30.10179 | 34.63484 | 26.32037 | 1.31589 | 2.00200  |
| 15 | 0.00004 | 2374266.66667 | 587.67266  | 319.90646 | 32.10110 | 30.24301 | 34.93934 | 26.62487 | 1.31228 | 2.20400  |
| 16 | 0.00005 | 2467300.00000 | 624.46075  | 333.12162 | 32.38732 | 30.44167 | 35.34989 | 27.03541 | 1.30754 | 2.42078  |
| 17 | 0.00005 | 2594133.33333 | 671.89777  | 349.15996 | 32.73832 | 30.70412 | 35.86549 | 27.55102 | 1.30178 | 2.68256  |
| 18 | 0.00005 | 2757066.66667 | 731.16684  | 367.69380 | 33.14983 | 31.03874 | 36.48693 | 28.17246 | 1.29513 | 2.96992  |
| 19 | 0.00005 | 2960833.33333 | 804.69086  | 388.51754 | 33.62154 | 31.45860 | 37.22124 | 28.90677 | 1.28763 | 3.37356  |
| 20 | 0.00005 | 3204900.00000 | 893.18728  | 410.67528 | 34.13741 | 31.96220 | 38.04971 | 29.73524 | 1.27962 | 3.82275  |
| 21 | 0.00005 | 3486166.66667 | 996.85080  | 433.05050 | 34.67749 | 32.53759 | 38.94230 | 30.62783 | 1.27147 | 4.34919  |
| 22 | 0.00005 | 3788133.33333 | 1111.71841 | 453.99591 | 35.20563 | 33.14322 | 39.83466 | 31.52019 | 1.26378 | 4.91015  |
| 23 | 0.00005 | 4092800.00000 | 1233.31549 | 472.59928 | 35.69642 | 33.73529 | 40.67388 | 32.35940 | 1.25694 | 5.55606  |
| 24 | 0.00006 | 4388500.00000 | 1358.40034 | 488.86113 | 36.14051 | 34.28277 | 41.43387 | 33.11940 | 1.25105 | 6.23376  |
| 25 | 0.00006 | 4667033.33333 | 1484.44110 | 503.30674 | 36.53731 | 34.76667 | 42.10758 | 33.79310 | 1.24604 | 6.92748  |
| 26 | 0.00006 | 4917800.00000 | 1607.53812 | 516.51550 | 36.88563 | 35.17309 | 42.69254 | 34.37807 | 1.24185 | 7.57202  |
| 27 | 0.00006 | 5130433.33333 | 1723.68423 | 529.03050 | 37.18632 | 35.49886 | 43.19456 | 34.88009 | 1.23837 | 8.18931  |
| 28 | 0.00006 | 5289300.00000 | 1826.91347 | 540.85848 | 37.43570 | 35.74460 | 43.61346 | 35.29899 | 1.23554 | 8.80467  |
| 29 | 0.00006 | 5384366.66667 | 1912.00126 | 551.52311 | 37.63126 | 35.91886 | 43.94828 | 35.63381 | 1.23333 | 9.28609  |
| 30 | 0.00007 | 5415833.33333 | 1977.24274 | 560.47285 | 37.77626 | 36.03672 | 44.20323 | 35.88876 | 1.23167 | 9.66618  |
| 31 | 0.00007 | 5390466.66667 | 2023.59991 | 567.32646 | 37.87709 | 36.11284 | 44.38535 | 36.07088 | 1.23050 | 9.99583  |
| 32 | 0.00007 | 5319066.66667 | 2052.86422 | 571.89110 | 37.93992 | 36.15786 | 44.50133 | 36.18686 | 1.22976 | 10.12051 |
| 33 | 0.00007 | 5214200.00000 | 2068.80827 | 574.46124 | 37.97390 | 36.18144 | 44.56497 | 36.25050 | 1.22936 | 10.21727 |
| 34 | 0.00007 | 5085933.33333 | 2074.36384 | 575.37108 | 37.98570 | 36.18950 | 44.58723 | 36.27276 | 1.22922 | 10.24863 |
| 35 | 0.00008 | 4945133.33333 | 2073.20025 | 575.17990 | 37.98323 | 36.18782 | 44.58257 | 36.26809 | 1.22925 | 10.23169 |
| 36 | 0.00008 | 4800633.33333 | 2068.57817 | 574.42371 | 37.97341 | 36.18110 | 44.56405 | 36.24958 | 1.22937 | 10.18433 |
| 37 | 0.00008 | 4654066.66667 | 2060.45148 | 573.10663 | 37.95611 | 36.16916 | 44.53157 | 36.21710 | 1.22957 | 10.02198 |
| 38 | 0.00008 | 4507533.33333 | 2050.38238 | 571.49642 | 37.93461 | 36.15413 | 44.49145 | 36.17698 | 1.22983 | 9.98614  |
| 39 | 0.00008 | 4363366.66667 | 2038.58546 | 569.63976 | 37.90934 | 36.13618 | 44.44462 | 36.13015 | 1.23013 | 9.80234  |
| 40 | 0.00009 | 4222300.00000 | 2025.89861 | 567.67808 | 37.88205 | 36.11646 | 44.39443 | 36.07996 | 1.23045 | 9.70180  |
| 41 | 0.00009 | 4085800.00000 | 2012.81579 | 565.69213 | 37.85378 | 36.09567 | 44.34284 | 36.02837 | 1.23078 | 9.55431  |
| 42 | 0.00009 | 3957900.00000 | 2001.46099 | 563.99803 | 37.82914 | 36.07724 | 44.29818 | 35.98371 | 1.23106 | 9.41113  |
| 43 | 0.00009 | 3835166.66667 | 1990.30354 | 562.35934 | 37.80484 | 36.05878 | 44.25439 | 35.93992 | 1.23134 | 9.27375  |
| 44 | 0.00010 | 3721366.66667 | 1981.26510 | 561.05025 | 37.78507 | 36.04356 | 44.21898 | 35.90450 | 1.23157 | 9.10562  |
| 45 | 0.00010 | 3611366.66667 | 1972.04732 | 559.73171 | 37.76485 | 36.02780 | 44.18290 | 35.86843 | 1.23180 | 8.98260  |
| 46 | 0.00010 | 3505366.66667 | 1962.84435 | 558.43154 | 37.74458 | 36.01181 | 44.14691 | 35.83244 | 1.23204 | 8.86033  |

|    |         |               |            |           |          |          |          |          |         |         |
|----|---------|---------------|------------|-----------|----------|----------|----------|----------|---------|---------|
| 47 | 0.00010 | 3402866.66667 | 1953.27507 | 557.09640 | 37.72344 | 35.99492 | 44.10951 | 35.79504 | 1.23228 | 8.70437 |
| 48 | 0.00011 | 3305266.66667 | 1944.44347 | 555.87899 | 37.70385 | 35.97909 | 44.07502 | 35.76054 | 1.23250 | 8.58641 |
| 49 | 0.00011 | 3212866.66667 | 1936.31657 | 554.77097 | 37.68576 | 35.96431 | 44.04328 | 35.72881 | 1.23271 | 8.40839 |
| 50 | 0.00011 | 3124400.00000 | 1928.65468 | 553.73684 | 37.66865 | 35.95019 | 44.01335 | 35.69888 | 1.23291 | 8.30182 |
| 51 | 0.00011 | 3039233.33333 | 1920.83166 | 552.69122 | 37.65112 | 35.93558 | 43.98279 | 35.66832 | 1.23311 | 8.13600 |
| 52 | 0.00012 | 2956666.66667 | 1912.84179 | 551.63376 | 37.63315 | 35.92046 | 43.95157 | 35.63710 | 1.23331 | 8.03451 |
| 53 | 0.00012 | 2876966.66667 | 1904.60204 | 550.55400 | 37.61456 | 35.90465 | 43.91935 | 35.60488 | 1.23352 | 7.87540 |
| 54 | 0.00012 | 2800133.33333 | 1896.21526 | 549.46594 | 37.59557 | 35.88834 | 43.88653 | 35.57206 | 1.23374 | 7.72086 |
| 55 | 0.00012 | 2725933.33333 | 1887.92867 | 548.40143 | 37.57673 | 35.87200 | 43.85407 | 35.53960 | 1.23395 | 7.62597 |
| 56 | 0.00013 | 2654066.66667 | 1879.15771 | 547.28581 | 37.55671 | 35.85446 | 43.81967 | 35.50520 | 1.23418 | 7.45130 |
| 57 | 0.00013 | 2584833.33333 | 1870.50386 | 546.19596 | 37.53688 | 35.83690 | 43.78568 | 35.47121 | 1.23440 | 7.33446 |
| 58 | 0.00013 | 2517766.66667 | 1861.57026 | 545.08184 | 37.51632 | 35.81852 | 43.75053 | 35.43606 | 1.23463 | 7.19467 |
| 59 | 0.00014 | 2453166.66667 | 1852.52644 | 543.96496 | 37.49542 | 35.79962 | 43.71488 | 35.40041 | 1.23487 | 7.03387 |
| 60 | 0.00014 | 2391133.33333 | 1843.82221 | 542.90009 | 37.47521 | 35.78118 | 43.68050 | 35.36602 | 1.23510 | 6.92735 |
| 61 | 0.00014 | 2331466.66667 | 1835.13175 | 541.84644 | 37.45494 | 35.76250 | 43.64609 | 35.33161 | 1.23533 | 6.77693 |
| 62 | 0.00014 | 2272800.00000 | 1825.58780 | 540.69987 | 37.43258 | 35.74169 | 43.60819 | 35.29372 | 1.23558 | 6.65317 |
| 63 | 0.00015 | 2215833.33333 | 1815.79270 | 539.53417 | 37.40952 | 35.71999 | 43.56919 | 35.25471 | 1.23584 | 6.53096 |
| 64 | 0.00015 | 2161000.00000 | 1805.93131 | 538.37140 | 37.38618 | 35.69781 | 43.52978 | 35.21531 | 1.23610 | 6.36829 |
| 65 | 0.00015 | 2108100.00000 | 1796.17225 | 537.23091 | 37.36295 | 35.67551 | 43.49065 | 35.17617 | 1.23637 | 6.25423 |
| 66 | 0.00016 | 2057400.00000 | 1786.82421 | 536.14753 | 37.34059 | 35.65382 | 43.45302 | 35.13855 | 1.23662 | 6.14411 |
| 67 | 0.00016 | 2008200.00000 | 1777.13525 | 535.03356 | 37.31728 | 35.63101 | 43.41386 | 35.09939 | 1.23688 | 5.99676 |
| 68 | 0.00016 | 1961033.33333 | 1767.76954 | 533.96495 | 37.29464 | 35.60863 | 43.37585 | 35.06138 | 1.23714 | 5.87447 |
| 69 | 0.00016 | 1915533.33333 | 1758.48327 | 532.91295 | 37.27206 | 35.58612 | 43.33800 | 35.02353 | 1.23740 | 5.75670 |
| 70 | 0.00017 | 1871733.33333 | 1749.27843 | 531.87718 | 37.24955 | 35.56348 | 43.30031 | 34.98584 | 1.23765 | 5.62409 |
| 71 | 0.00017 | 1829566.66667 | 1740.27812 | 530.87078 | 37.22743 | 35.54104 | 43.26329 | 34.94882 | 1.23790 | 5.51494 |
| 72 | 0.00017 | 1788500.00000 | 1730.94077 | 529.83293 | 37.20435 | 35.51743 | 43.22469 | 34.91022 | 1.23817 | 5.39092 |
| 73 | 0.00018 | 1749733.33333 | 1722.60015 | 528.91091 | 37.18362 | 35.49606 | 43.19005 | 34.87558 | 1.23840 | 5.28966 |
| 74 | 0.00018 | 1713500.00000 | 1715.50288 | 528.12985 | 37.16589 | 35.47767 | 43.16044 | 34.84597 | 1.23861 | 5.17753 |
| 75 | 0.00018 | 1678500.00000 | 1708.45251 | 527.35695 | 37.14820 | 35.45920 | 43.13090 | 34.81643 | 1.23881 | 5.07104 |
| 76 | 0.00019 | 1644833.33333 | 1701.61418 | 526.61000 | 37.13097 | 35.44110 | 43.10213 | 34.78766 | 1.23901 | 4.96838 |
| 77 | 0.00019 | 1612300.00000 | 1694.84436 | 525.87297 | 37.11384 | 35.42300 | 43.07353 | 34.75906 | 1.23920 | 4.86941 |
| 78 | 0.00019 | 1581033.33333 | 1688.34214 | 525.16722 | 37.09731 | 35.40545 | 43.04594 | 34.73147 | 1.23939 | 4.77403 |
| 79 | 0.00019 | 1550566.66667 | 1681.57827 | 524.43515 | 37.08004 | 35.38701 | 43.01713 | 34.70265 | 1.23959 | 4.66608 |
| 80 | 0.00020 | 1521033.33333 | 1674.82939 | 523.70666 | 37.06273 | 35.36843 | 42.98824 | 34.67377 | 1.23979 | 4.57668 |
| 81 | 0.00020 | 1492333.33333 | 1667.94703 | 522.96561 | 37.04500 | 35.34930 | 42.95865 | 34.64418 | 1.24000 | 4.47485 |
| 82 | 0.00020 | 1464766.66667 | 1661.39934 | 522.26217 | 37.02805 | 35.33092 | 42.93037 | 34.61590 | 1.24019 | 4.39129 |
| 83 | 0.00021 | 1438000.00000 | 1654.69865 | 521.54374 | 37.01063 | 35.31193 | 42.90129 | 34.58682 | 1.24039 | 4.28158 |
| 84 | 0.00021 | 1412166.66667 | 1648.20652 | 520.84892 | 36.99367 | 35.29336 | 42.87299 | 34.55852 | 1.24059 | 4.20400 |
| 85 | 0.00021 | 1387133.33333 | 1641.81120 | 520.16552 | 36.97689 | 35.27489 | 42.84498 | 34.53051 | 1.24079 | 4.12897 |
| 86 | 0.00022 | 1362966.66667 | 1635.48017 | 519.48990 | 36.96020 | 35.25645 | 42.81712 | 34.50265 | 1.24098 | 4.02890 |
| 87 | 0.00022 | 1339700.00000 | 1629.30452 | 518.83161 | 36.94385 | 35.23831 | 42.78982 | 34.47534 | 1.24117 | 3.93238 |
| 88 | 0.00022 | 1317433.33333 | 1623.60605 | 518.22473 | 36.92870 | 35.22142 | 42.76451 | 34.45004 | 1.24135 | 3.86613 |
| 89 | 0.00022 | 1295266.66667 | 1617.16519 | 517.53929 | 36.91150 | 35.20218 | 42.73577 | 34.42130 | 1.24155 | 3.77535 |
| 90 | 0.00023 | 1274300.00000 | 1611.45626 | 516.93209 | 36.89618 | 35.18498 | 42.71018 | 34.39570 | 1.24173 | 3.70018 |
| 91 | 0.00023 | 1253933.33333 | 1605.77223 | 516.32777 | 36.88087 | 35.16772 | 42.68458 | 34.37011 | 1.24191 | 3.62801 |
| 92 | 0.00023 | 1234300.00000 | 1600.24935 | 515.74070 | 36.86593 | 35.15082 | 42.65960 | 34.34513 | 1.24209 | 3.54573 |
| 93 | 0.00024 | 1215433.33333 | 1594.97290 | 515.17987 | 36.85160 | 35.13455 | 42.63563 | 34.32116 | 1.24226 | 3.46637 |
| 94 | 0.00024 | 1197133.33333 | 1589.71992 | 514.62149 | 36.83728 | 35.11824 | 42.61166 | 34.29719 | 1.24242 | 3.38966 |
| 95 | 0.00024 | 1179333.33333 | 1584.49937 | 514.06644 | 36.82298 | 35.10192 | 42.58774 | 34.27327 | 1.24259 | 3.32705 |
| 96 | 0.00024 | 1162333.33333 | 1579.68057 | 513.55394 | 36.80974 | 35.08675 | 42.56557 | 34.25109 | 1.24275 | 3.25492 |
| 97 | 0.00025 | 1145500.00000 | 1574.43592 | 512.99590 | 36.79527 | 35.07013 | 42.54133 | 34.22686 | 1.24292 | 3.18481 |
| 98 | 0.00025 | 1129166.66667 | 1569.24201 | 512.44294 | 36.78088 | 35.05356 | 42.51723 | 34.20276 | 1.24309 | 3.11629 |

|     |         |               |            |           |          |          |          |          |         |         |
|-----|---------|---------------|------------|-----------|----------|----------|----------|----------|---------|---------|
| 99  | 0.00025 | 1113300.00000 | 1564.01831 | 511.88640 | 36.76636 | 35.03678 | 42.49288 | 34.17840 | 1.24327 | 3.03854 |
| 100 | 0.00025 | 1098233.33333 | 1559.38969 | 511.39287 | 36.75343 | 35.02181 | 42.47121 | 34.15674 | 1.24342 | 2.98557 |
| 101 | 0.00026 | 1083600.00000 | 1554.74783 | 510.89750 | 36.74043 | 35.00670 | 42.44939 | 34.13492 | 1.24358 | 2.91275 |
| 102 | 0.00026 | 1069000.00000 | 1549.59923 | 510.34750 | 36.72594 | 34.98985 | 42.42509 | 34.11061 | 1.24375 | 2.85220 |
| 103 | 0.00026 | 1054933.33333 | 1544.68238 | 509.82164 | 36.71206 | 34.97364 | 42.40177 | 34.08730 | 1.24392 | 2.79297 |
| 104 | 0.00027 | 1041600.00000 | 1540.26313 | 509.34844 | 36.69953 | 34.95899 | 42.38074 | 34.06626 | 1.24407 | 2.72549 |
| 105 | 0.00027 | 1028600.00000 | 1535.84021 | 508.87427 | 36.68695 | 34.94424 | 42.35960 | 34.04512 | 1.24422 | 2.67056 |
| 106 | 0.00027 | 1016066.66667 | 1531.57667 | 508.41660 | 36.67477 | 34.92994 | 42.33914 | 34.02467 | 1.24437 | 2.60695 |
| 107 | 0.00027 | 1003900.00000 | 1527.40257 | 507.96792 | 36.66282 | 34.91587 | 42.31903 | 34.00456 | 1.24451 | 2.55526 |
| 108 | 0.00028 | 991900.00000  | 1522.97508 | 507.49133 | 36.65009 | 34.90086 | 42.29763 | 33.98316 | 1.24466 | 2.49475 |
| 109 | 0.00028 | 980666.66667  | 1519.29142 | 507.09423 | 36.63946 | 34.88831 | 42.27975 | 33.96528 | 1.24479 | 2.44598 |
| 110 | 0.00028 | 969300.00000  | 1514.92641 | 506.62297 | 36.62683 | 34.87336 | 42.25849 | 33.94402 | 1.24495 | 2.38871 |
| 111 | 0.00028 | 958200.00000  | 1510.51086 | 506.14543 | 36.61400 | 34.85816 | 42.23689 | 33.92242 | 1.24510 | 2.33227 |
| 112 | 0.00029 | 947466.66667  | 1506.22012 | 505.68056 | 36.60150 | 34.84330 | 42.21583 | 33.90135 | 1.24525 | 2.27727 |
| 113 | 0.00029 | 937033.33333  | 1501.96738 | 505.21894 | 36.58905 | 34.82850 | 42.19486 | 33.88039 | 1.24541 | 2.22371 |
| 114 | 0.00029 | 926800.00000  | 1497.65982 | 504.75047 | 36.57641 | 34.81343 | 42.17354 | 33.85907 | 1.24556 | 2.18069 |
| 115 | 0.00029 | 917000.00000  | 1493.58647 | 504.30660 | 36.56440 | 34.79910 | 42.15330 | 33.83883 | 1.24571 | 2.12037 |
| 116 | 0.00029 | 907866.66667  | 1490.25484 | 503.94289 | 36.55456 | 34.78733 | 42.13669 | 33.82222 | 1.24583 | 2.08035 |
| 117 | 0.00030 | 898866.66667  | 1486.71097 | 503.55534 | 36.54405 | 34.77475 | 42.11896 | 33.80449 | 1.24596 | 2.02354 |
| 118 | 0.00030 | 890266.66667  | 1483.50950 | 503.20462 | 36.53453 | 34.76335 | 42.10290 | 33.78842 | 1.24607 | 1.98594 |
| 119 | 0.00030 | 881733.33333  | 1480.01029 | 502.82059 | 36.52410 | 34.75083 | 42.08528 | 33.77081 | 1.24620 | 1.93148 |
| 120 | 0.00030 | 873566.66667  | 1476.82605 | 502.47049 | 36.51458 | 34.73939 | 42.06920 | 33.75473 | 1.24632 | 1.89572 |
| 121 | 0.00031 | 865366.66667  | 1473.19523 | 502.07052 | 36.50369 | 34.72630 | 42.05080 | 33.73633 | 1.24645 | 1.84327 |
| 122 | 0.00031 | 857666.66667  | 1470.08411 | 501.72713 | 36.49433 | 34.71503 | 42.03499 | 33.72051 | 1.24657 | 1.80057 |
| 123 | 0.00031 | 849966.66667  | 1466.65127 | 501.34749 | 36.48398 | 34.70255 | 42.01748 | 33.70301 | 1.24670 | 1.75886 |
| 124 | 0.00031 | 842766.66667  | 1463.76901 | 501.02813 | 36.47526 | 34.69203 | 42.00274 | 33.68827 | 1.24681 | 1.71812 |
| 125 | 0.00031 | 835566.66667  | 1460.53730 | 500.66938 | 36.46546 | 34.68020 | 41.98616 | 33.67169 | 1.24693 | 1.66994 |
| 126 | 0.00032 | 828700.00000  | 1457.63969 | 500.34708 | 36.45665 | 34.66955 | 41.97125 | 33.65678 | 1.24704 | 1.63930 |
| 127 | 0.00032 | 821766.66667  | 1454.28986 | 499.97373 | 36.44644 | 34.65719 | 41.95396 | 33.63949 | 1.24716 | 1.59270 |
| 128 | 0.00032 | 815200.00000  | 1451.26175 | 499.63553 | 36.43718 | 34.64598 | 41.93829 | 33.62382 | 1.24728 | 1.54693 |
| 129 | 0.00032 | 808600.00000  | 1447.94532 | 499.26434 | 36.42701 | 34.63365 | 41.92106 | 33.60659 | 1.24741 | 1.51825 |
| 130 | 0.00032 | 802200.00000  | 1444.67248 | 498.89720 | 36.41695 | 34.62144 | 41.90401 | 33.58954 | 1.24753 | 1.47388 |
| 131 | 0.00032 | 795933.33333  | 1441.37730 | 498.52670 | 36.40678 | 34.60910 | 41.88679 | 33.57232 | 1.24766 | 1.43832 |
| 132 | 0.00033 | 790000.00000  | 1438.38705 | 498.18973 | 36.39753 | 34.59786 | 41.87111 | 33.55664 | 1.24777 | 1.39562 |
| 133 | 0.00033 | 783900.00000  | 1434.84406 | 497.78953 | 36.38654 | 34.58449 | 41.85248 | 33.53801 | 1.24791 | 1.36142 |
| 134 | 0.00033 | 778133.33333  | 1431.66651 | 497.42971 | 36.37666 | 34.57245 | 41.83571 | 33.52124 | 1.24804 | 1.32773 |
| 135 | 0.00033 | 772533.33333  | 1428.51550 | 497.07205 | 36.36683 | 34.56047 | 41.81903 | 33.50456 | 1.24816 | 1.28705 |
| 136 | 0.00033 | 766933.33333  | 1425.13247 | 496.68710 | 36.35624 | 34.54756 | 41.80106 | 33.48659 | 1.24829 | 1.25467 |
| 137 | 0.00033 | 761633.33333  | 1422.08038 | 496.33893 | 36.34666 | 34.53587 | 41.78480 | 33.47033 | 1.24841 | 1.22285 |
| 138 | 0.00034 | 756533.33333  | 1419.14014 | 496.00273 | 36.33741 | 34.52457 | 41.76909 | 33.45462 | 1.24853 | 1.18417 |
| 139 | 0.00034 | 751400.00000  | 1415.92262 | 495.63391 | 36.32725 | 34.51217 | 41.75184 | 33.43737 | 1.24866 | 1.15357 |
| 140 | 0.00034 | 746600.00000  | 1413.08190 | 495.30749 | 36.31826 | 34.50117 | 41.73657 | 33.42210 | 1.24877 | 1.11601 |
| 141 | 0.00034 | 741933.33333  | 1410.29073 | 494.98601 | 36.30941 | 34.49034 | 41.72152 | 33.40705 | 1.24888 | 1.08663 |
| 142 | 0.00034 | 737400.00000  | 1407.51359 | 494.66541 | 36.30057 | 34.47953 | 41.70651 | 33.39203 | 1.24900 | 1.05033 |
| 143 | 0.00034 | 732766.66667  | 1404.35037 | 494.29931 | 36.29048 | 34.46717 | 41.68935 | 33.37488 | 1.24912 | 1.02177 |
| 144 | 0.00034 | 728733.33333  | 1402.10730 | 494.03911 | 36.28331 | 34.45838 | 41.67716 | 33.36268 | 1.24921 | 0.98651 |
| 145 | 0.00035 | 724266.66667  | 1398.84529 | 493.65981 | 36.27285 | 34.44556 | 41.65937 | 33.34490 | 1.24935 | 0.95898 |
| 146 | 0.00035 | 720133.33333  | 1396.04329 | 493.33313 | 36.26385 | 34.43451 | 41.64404 | 33.32957 | 1.24946 | 0.93164 |
| 147 | 0.00035 | 715600.00000  | 1392.24384 | 492.88887 | 36.25159 | 34.41947 | 41.62319 | 33.30872 | 1.24962 | 0.89733 |
| 148 | 0.00035 | 711300.00000  | 1388.71777 | 492.47520 | 36.24019 | 34.40546 | 41.60377 | 33.28930 | 1.24976 | 0.87041 |
| 149 | 0.00035 | 707100.00000  | 1385.17136 | 492.05781 | 36.22867 | 34.39131 | 41.58417 | 33.26969 | 1.24991 | 0.83686 |
| 150 | 0.00035 | 702933.33333  | 1381.47836 | 491.62170 | 36.21664 | 34.37652 | 41.56368 | 33.24920 | 1.25007 | 0.80372 |

|     |         |              |            |           |          |          |          |          |         |          |
|-----|---------|--------------|------------|-----------|----------|----------|----------|----------|---------|----------|
| 151 | 0.00035 | 698633.33333 | 1377.35260 | 491.13270 | 36.20315 | 34.35993 | 41.54069 | 33.22622 | 1.25024 | 0.77787  |
| 152 | 0.00035 | 694266.66667 | 1372.92558 | 490.60585 | 36.18862 | 34.34204 | 41.51593 | 33.20145 | 1.25042 | 0.75217  |
| 153 | 0.00036 | 690133.33333 | 1368.75483 | 490.10744 | 36.17487 | 34.32512 | 41.49249 | 33.17802 | 1.25060 | 0.71989  |
| 154 | 0.00036 | 685966.66667 | 1364.35506 | 489.57943 | 36.16031 | 34.30718 | 41.46766 | 33.15319 | 1.25079 | 0.69493  |
| 155 | 0.00036 | 681933.33333 | 1360.02215 | 489.05719 | 36.14591 | 34.28943 | 41.44309 | 33.12862 | 1.25098 | 0.66343  |
| 156 | 0.00036 | 677600.00000 | 1354.93230 | 488.44079 | 36.12892 | 34.26848 | 41.41410 | 33.09963 | 1.25120 | 0.63898  |
| 157 | 0.00036 | 673633.33333 | 1350.38184 | 487.88698 | 36.11366 | 34.24965 | 41.38805 | 33.07358 | 1.25139 | 0.60806  |
| 158 | 0.00036 | 669100.00000 | 1344.54081 | 487.17224 | 36.09397 | 34.22536 | 41.35443 | 33.03996 | 1.25165 | 0.58409  |
| 159 | 0.00036 | 664633.33333 | 1338.64180 | 486.44591 | 36.07397 | 34.20068 | 41.32027 | 33.00580 | 1.25191 | 0.55350  |
| 160 | 0.00036 | 659966.66667 | 1332.15047 | 485.64130 | 36.05184 | 34.17334 | 41.28244 | 32.96797 | 1.25220 | 0.52322  |
| 161 | 0.00036 | 654666.66667 | 1324.22729 | 484.65142 | 36.02462 | 34.13973 | 41.23592 | 32.92145 | 1.25255 | 0.49956  |
| 162 | 0.00036 | 649100.00000 | 1315.61004 | 483.56482 | 35.99479 | 34.10288 | 41.18489 | 32.87042 | 1.25295 | 0.47587  |
| 163 | 0.00036 | 643133.33333 | 1305.99163 | 482.33927 | 35.96118 | 34.06137 | 41.12740 | 32.81293 | 1.25339 | 0.44582  |
| 164 | 0.00036 | 636400.00000 | 1294.66103 | 480.87776 | 35.92118 | 34.01198 | 41.05892 | 32.74445 | 1.25392 | 0.42225  |
| 165 | 0.00037 | 629033.33333 | 1281.84976 | 479.20118 | 35.87539 | 33.95548 | 40.98053 | 32.66606 | 1.25453 | 0.39228  |
| 166 | 0.00037 | 621166.66667 | 1267.86299 | 477.34035 | 35.82473 | 33.89301 | 40.89374 | 32.57926 | 1.25521 | 0.36881  |
| 167 | 0.00037 | 612333.33333 | 1251.71160 | 475.15027 | 35.76531 | 33.81988 | 40.79193 | 32.47746 | 1.25601 | 0.33921  |
| 168 | 0.00037 | 603200.00000 | 1234.75727 | 472.80146 | 35.70187 | 33.74197 | 40.68321 | 32.36874 | 1.25687 | 0.30996  |
| 169 | 0.00037 | 593100.00000 | 1215.67023 | 470.09301 | 35.62910 | 33.65288 | 40.55850 | 32.24403 | 1.25786 | 0.28711  |
| 170 | 0.00037 | 581900.00000 | 1194.17414 | 466.95705 | 35.54536 | 33.55082 | 40.41508 | 32.10061 | 1.25901 | 0.26437  |
| 171 | 0.00037 | 569700.00000 | 1170.44004 | 463.38325 | 35.45066 | 33.43607 | 40.25299 | 31.93851 | 1.26033 | 0.23608  |
| 172 | 0.00037 | 556700.00000 | 1144.88053 | 459.39629 | 35.34594 | 33.31013 | 40.07396 | 31.75949 | 1.26179 | 0.20838  |
| 173 | 0.00037 | 542733.33333 | 1117.18656 | 454.90477 | 35.22912 | 33.17101 | 39.87467 | 31.56020 | 1.26345 | 0.18690  |
| 174 | 0.00037 | 528633.33333 | 1089.04699 | 450.14720 | 35.10672 | 33.02693 | 39.66641 | 31.35194 | 1.26520 | 0.16071  |
| 175 | 0.00037 | 513400.00000 | 1058.43763 | 444.73697 | 34.96914 | 32.86727 | 39.43316 | 31.11869 | 1.26719 | 0.14067  |
| 176 | 0.00037 | 497733.33333 | 1026.80509 | 438.87322 | 34.82189 | 32.69927 | 39.18467 | 30.87020 | 1.26934 | 0.12134  |
| 177 | 0.00037 | 481200.00000 | 993.20736  | 432.32366 | 34.65959 | 32.51777 | 38.91235 | 30.59787 | 1.27173 | 0.09300  |
| 178 | 0.00037 | 464166.66667 | 958.49028  | 425.18759 | 34.48516 | 32.32725 | 38.62177 | 30.30730 | 1.27434 | 0.08036  |
| 179 | 0.00037 | 446866.66667 | 923.06537  | 417.49801 | 34.29981 | 32.13017 | 38.31559 | 30.00112 | 1.27714 | 0.05466  |
| 180 | 0.00037 | 429066.66667 | 886.51236  | 409.10737 | 34.10035 | 31.92449 | 37.98936 | 29.67488 | 1.28019 | 0.03942  |
| 181 | 0.00037 | 411233.33333 | 849.80379  | 400.18950 | 33.89125 | 31.71614 | 37.65121 | 29.33673 | 1.28342 | 0.02521  |
| 182 | 0.00037 | 392800.00000 | 811.75556  | 390.39899 | 33.66474 | 31.49899 | 37.28962 | 28.97515 | 1.28695 | 0.00804  |
| 183 | 0.00037 | 374366.66667 | 773.61971  | 379.99856 | 33.42722 | 31.28092 | 36.91595 | 28.60148 | 1.29070 | -0.00767 |
| 184 | 0.00037 | 356266.66667 | 736.11714  | 369.16930 | 33.18291 | 31.06691 | 36.53766 | 28.22319 | 1.29460 | -0.01827 |
| 185 | 0.00037 | 338466.66667 | 699.18782  | 357.89560 | 32.93142 | 30.85749 | 36.15483 | 27.84036 | 1.29865 | -0.02779 |
| 186 | 0.00037 | 321500.00000 | 663.90581  | 346.53480 | 32.68057 | 30.65950 | 35.77974 | 27.46527 | 1.30273 | -0.04290 |
| 187 | 0.00037 | 305600.00000 | 630.81624  | 335.33486 | 32.43551 | 30.47647 | 35.41988 | 27.10541 | 1.30675 | -0.04703 |
| 188 | 0.00037 | 291633.33333 | 601.66110  | 325.01347 | 32.21142 | 30.31796 | 35.09652 | 26.78205 | 1.31045 | -0.05972 |
| 189 | 0.00037 | 279466.66667 | 576.20187  | 315.64218 | 32.00926 | 30.18214 | 34.80949 | 26.49502 | 1.31381 | -0.06568 |
| 190 | 0.00037 | 269033.33333 | 554.28540  | 307.30002 | 31.83024 | 30.06746 | 34.55903 | 26.24456 | 1.31681 | -0.07405 |
| 191 | 0.00037 | 260900.00000 | 537.09188  | 300.57343 | 31.68650 | 29.97913 | 34.36042 | 26.04595 | 1.31922 | -0.07949 |
| 192 | 0.00037 | 253800.00000 | 521.99446  | 294.53230 | 31.55783 | 29.90287 | 34.18452 | 25.87005 | 1.32139 | -0.08750 |
| 193 | 0.00037 | 248200.00000 | 509.96468  | 289.62716 | 31.45364 | 29.84305 | 34.04339 | 25.72892 | 1.32316 | -0.09287 |
| 194 | 0.00037 | 242733.33333 | 498.17753  | 284.74116 | 31.35009 | 29.78528 | 33.90428 | 25.58981 | 1.32491 | -0.10064 |
| 195 | 0.00037 | 237633.33333 | 487.11406  | 280.08237 | 31.25158 | 29.73188 | 33.77299 | 25.45851 | 1.32659 | -0.10808 |
| 196 | 0.00037 | 232333.33333 | 475.62785  | 275.17011 | 31.14792 | 29.67730 | 33.63595 | 25.32147 | 1.32836 | -0.11279 |
| 197 | 0.00037 | 226866.66667 | 463.77866  | 270.02105 | 31.03950 | 29.62199 | 33.49381 | 25.17934 | 1.33021 | -0.11939 |
| 198 | 0.00037 | 221733.33333 | 452.59217  | 265.08299 | 30.93574 | 29.57072 | 33.35894 | 25.04447 | 1.33199 | -0.12561 |
| 199 | 0.00037 | 216133.33333 | 440.45050  | 259.63757 | 30.82156 | 29.51618 | 33.21181 | 24.89734 | 1.33395 | -0.12917 |
| 200 | 0.00036 | 211000.00000 | 429.24808  | 254.53323 | 30.71474 | 29.46692 | 33.07539 | 24.76092 | 1.33579 | -0.13455 |
| 201 | 0.00036 | 206200.00000 | 418.71268  | 249.66168 | 30.61299 | 29.42157 | 32.94653 | 24.63205 | 1.33755 | -0.13976 |
| 202 | 0.00036 | 201833.33333 | 409.05769  | 245.13593 | 30.51862 | 29.38086 | 32.82796 | 24.51348 | 1.33918 | -0.14281 |

|     |         |              |           |           |          |          |          |          |         |          |
|-----|---------|--------------|-----------|-----------|----------|----------|----------|----------|---------|----------|
| 203 | 0.00036 | 197500.00000 | 399.46017 | 240.57831 | 30.42375 | 29.34125 | 32.70965 | 24.39518 | 1.34082 | -0.14775 |
| 204 | 0.00036 | 193700.00000 | 390.93171 | 236.47859 | 30.33854 | 29.30678 | 32.60417 | 24.28970 | 1.34230 | -0.15257 |
| 205 | 0.00036 | 189800.00000 | 382.20317 | 232.23363 | 30.25044 | 29.27224 | 32.49587 | 24.18140 | 1.34384 | -0.15532 |
| 206 | 0.00036 | 186133.33333 | 373.93715 | 228.16733 | 30.16618 | 29.24024 | 32.39300 | 24.07853 | 1.34531 | -0.15977 |
| 207 | 0.00036 | 182433.33333 | 365.59840 | 224.01910 | 30.08034 | 29.20867 | 32.28892 | 23.97445 | 1.34681 | -0.16401 |
| 208 | 0.00036 | 178933.33333 | 357.66624 | 220.02962 | 29.99790 | 29.17932 | 32.18964 | 23.87517 | 1.34825 | -0.16623 |
| 209 | 0.00036 | 175533.33333 | 349.93022 | 216.09742 | 29.91676 | 29.15137 | 32.09256 | 23.77809 | 1.34967 | -0.17014 |
| 210 | 0.00036 | 172200.00000 | 342.32473 | 212.19127 | 29.83627 | 29.12454 | 31.99688 | 23.68241 | 1.35108 | -0.17387 |
| 211 | 0.00036 | 169133.33333 | 335.24733 | 208.52000 | 29.76073 | 29.10016 | 31.90763 | 23.59316 | 1.35241 | -0.17749 |
| 212 | 0.00035 | 165933.33333 | 327.91423 | 204.67867 | 29.68179 | 29.07553 | 31.81494 | 23.50047 | 1.35380 | -0.17926 |
| 213 | 0.00035 | 163033.33333 | 321.17401 | 201.11389 | 29.60864 | 29.05346 | 31.72957 | 23.41510 | 1.35509 | -0.18258 |
| 214 | 0.00035 | 160300.00000 | 314.76123 | 197.69164 | 29.53850 | 29.03298 | 31.64817 | 23.33370 | 1.35633 | -0.18592 |
| 215 | 0.00035 | 157900.00000 | 309.00949 | 194.59642 | 29.47515 | 29.01505 | 31.57503 | 23.26056 | 1.35745 | -0.18774 |
| 216 | 0.00035 | 155500.00000 | 303.25465 | 191.47485 | 29.41134 | 28.99753 | 31.50173 | 23.18725 | 1.35858 | -0.19117 |
| 217 | 0.00035 | 152933.33333 | 297.17445 | 188.14963 | 29.34345 | 28.97948 | 31.42414 | 23.10967 | 1.35978 | -0.19431 |
| 218 | 0.00035 | 150533.33333 | 291.41943 | 184.97617 | 29.27875 | 28.96285 | 31.35057 | 23.03610 | 1.36093 | -0.19725 |
| 219 | 0.00035 | 148133.33333 | 285.67443 | 181.78258 | 29.21374 | 28.94669 | 31.27700 | 22.96253 | 1.36209 | -0.19861 |
| 220 | 0.00034 | 145900.00000 | 280.25266 | 178.74481 | 29.15198 | 28.93186 | 31.20745 | 22.89298 | 1.36319 | -0.20141 |
| 221 | 0.00034 | 143666.66667 | 274.83297 | 175.68467 | 29.08985 | 28.91743 | 31.13782 | 22.82335 | 1.36430 | -0.20414 |
| 222 | 0.00034 | 141700.00000 | 269.92483 | 172.89276 | 29.03325 | 28.90473 | 31.07466 | 22.76019 | 1.36531 | -0.20689 |
| 223 | 0.00034 | 139633.33333 | 264.83545 | 169.97672 | 28.97422 | 28.89192 | 31.00907 | 22.69460 | 1.36636 | -0.20819 |
| 224 | 0.00034 | 137700.00000 | 260.00126 | 167.18674 | 28.91783 | 28.88010 | 30.94667 | 22.63220 | 1.36737 | -0.21077 |
| 225 | 0.00034 | 136266.66667 | 256.10930 | 164.92604 | 28.87220 | 28.87083 | 30.89636 | 22.58189 | 1.36819 | -0.21369 |
| 226 | 0.00034 | 134500.00000 | 251.58868 | 162.28366 | 28.81894 | 28.86035 | 30.83785 | 22.52338 | 1.36915 | -0.21661 |
| 227 | 0.00033 | 132900.00000 | 247.38762 | 159.81190 | 28.76920 | 28.85088 | 30.78340 | 22.46893 | 1.37004 | -0.21793 |
| 228 | 0.00033 | 131300.00000 | 243.18636 | 157.32415 | 28.71921 | 28.84168 | 30.72887 | 22.41439 | 1.37094 | -0.22061 |
| 229 | 0.00033 | 129833.33333 | 239.23166 | 154.96763 | 28.67193 | 28.83328 | 30.67746 | 22.36299 | 1.37180 | -0.22327 |
| 230 | 0.00033 | 128100.00000 | 234.79468 | 152.30635 | 28.61863 | 28.82413 | 30.61970 | 22.30523 | 1.37276 | -0.22440 |
| 231 | 0.00033 | 126666.66667 | 230.91004 | 149.96095 | 28.57174 | 28.81638 | 30.56905 | 22.25458 | 1.37361 | -0.22674 |
| 232 | 0.00033 | 125200.00000 | 226.96549 | 147.56436 | 28.52392 | 28.80875 | 30.51754 | 22.20307 | 1.37447 | -0.22920 |
| 233 | 0.00032 | 123933.33333 | 223.39052 | 145.37894 | 28.48038 | 28.80206 | 30.47079 | 22.15632 | 1.37526 | -0.23045 |
| 234 | 0.00032 | 122633.33333 | 219.75459 | 143.14294 | 28.43592 | 28.79546 | 30.42317 | 22.10870 | 1.37607 | -0.23301 |
| 235 | 0.00032 | 121533.33333 | 216.48202 | 141.11865 | 28.39575 | 28.78971 | 30.38025 | 22.06578 | 1.37680 | -0.23440 |
| 236 | 0.00032 | 120233.33333 | 212.85207 | 138.86001 | 28.35101 | 28.78354 | 30.33257 | 22.01810 | 1.37762 | -0.23693 |
| 237 | 0.00032 | 119100.00000 | 209.51720 | 136.77234 | 28.30974 | 28.77806 | 30.28869 | 21.97422 | 1.37837 | -0.23933 |
| 238 | 0.00031 | 118133.33333 | 206.47919 | 134.85973 | 28.27201 | 28.77324 | 30.24866 | 21.93418 | 1.37906 | -0.24079 |
| 239 | 0.00031 | 117366.66667 | 203.78419 | 133.15427 | 28.23842 | 28.76909 | 30.21309 | 21.89862 | 1.37968 | -0.24374 |
| 240 | 0.00031 | 116400.00000 | 200.73597 | 131.21507 | 28.20032 | 28.76455 | 30.17280 | 21.85833 | 1.38038 | -0.24662 |
| 241 | 0.00031 | 115400.00000 | 197.64054 | 129.23449 | 28.16148 | 28.76010 | 30.13182 | 21.81735 | 1.38109 | -0.24687 |
| 242 | 0.00030 | 114633.33333 | 194.93375 | 127.49295 | 28.12741 | 28.75634 | 30.09592 | 21.78145 | 1.38172 | -0.25074 |
| 243 | 0.00030 | 113833.33333 | 192.17663 | 125.70956 | 28.09259 | 28.75265 | 30.05930 | 21.74483 | 1.38237 | -0.25131 |
| 244 | 0.00030 | 113333.33333 | 189.91664 | 124.24043 | 28.06397 | 28.74972 | 30.02923 | 21.71476 | 1.38289 | -0.25443 |
| 245 | 0.00030 | 112666.66667 | 187.36681 | 122.57480 | 28.03159 | 28.74653 | 29.99525 | 21.68078 | 1.38350 | -0.25764 |
| 246 | 0.00030 | 112033.33333 | 184.87019 | 120.93540 | 27.99980 | 28.74352 | 29.96192 | 21.64745 | 1.38409 | -0.25953 |
| 247 | 0.00029 | 111766.66667 | 182.97152 | 119.68286 | 27.97556 | 28.74130 | 29.93654 | 21.62206 | 1.38454 | -0.26185 |
| 248 | 0.00029 | 111433.33333 | 180.95289 | 118.34558 | 27.94973 | 28.73901 | 29.90951 | 21.59503 | 1.38502 | -0.26449 |
| 249 | 0.00029 | 111433.33333 | 179.46132 | 117.35367 | 27.93060 | 28.73737 | 29.88951 | 21.57503 | 1.38537 | -0.26744 |
| 250 | 0.00029 | 110933.33333 | 177.14645 | 115.80773 | 27.90086 | 28.73491 | 29.85842 | 21.54395 | 1.38593 | -0.27129 |
| 251 | 0.00028 | 110600.00000 | 175.09056 | 114.42794 | 27.87438 | 28.73280 | 29.83076 | 21.51629 | 1.38643 | -0.27359 |
| 252 | 0.00028 | 110433.33333 | 173.28693 | 113.21205 | 27.85109 | 28.73101 | 29.80645 | 21.49198 | 1.38686 | -0.27629 |
| 253 | 0.00028 | 110433.33333 | 171.72867 | 112.15740 | 27.83094 | 28.72952 | 29.78542 | 21.47095 | 1.38724 | -0.27940 |
| 254 | 0.00028 | 110433.33333 | 170.15809 | 111.09043 | 27.81059 | 28.72806 | 29.76419 | 21.44972 | 1.38763 | -0.28161 |

|     |         |              |           |           |          |          |          |          |         |          |
|-----|---------|--------------|-----------|-----------|----------|----------|----------|----------|---------|----------|
| 255 | 0.00027 | 110266.66667 | 168.30848 | 109.82864 | 27.78657 | 28.72640 | 29.73914 | 21.42467 | 1.38808 | -0.28581 |
| 256 | 0.00027 | 110433.33333 | 166.94919 | 108.89765 | 27.76889 | 28.72522 | 29.72071 | 21.40624 | 1.38841 | -0.28912 |
| 257 | 0.00027 | 110433.33333 | 165.32318 | 107.77976 | 27.74771 | 28.72385 | 29.69862 | 21.38415 | 1.38881 | -0.29154 |
| 258 | 0.00027 | 110600.00000 | 163.92572 | 106.81526 | 27.72947 | 28.72272 | 29.67961 | 21.36513 | 1.38916 | -0.29508 |
| 259 | 0.00026 | 110766.66667 | 162.50476 | 105.83092 | 27.71089 | 28.72160 | 29.66024 | 21.34577 | 1.38951 | -0.29884 |
| 260 | 0.00026 | 110766.66667 | 160.82442 | 104.66207 | 27.68889 | 28.72034 | 29.63730 | 21.32283 | 1.38993 | -0.30129 |
| 261 | 0.00026 | 110766.66667 | 159.12555 | 103.47488 | 27.66660 | 28.71911 | 29.61406 | 21.29959 | 1.39036 | -0.30461 |
| 262 | 0.00025 | 110600.00000 | 157.17747 | 102.10661 | 27.64098 | 28.71777 | 29.58735 | 21.27288 | 1.39085 | -0.30659 |
| 263 | 0.00025 | 110433.33333 | 155.21606 | 100.72126 | 27.61514 | 28.71649 | 29.56039 | 21.24592 | 1.39134 | -0.30945 |
| 264 | 0.00025 | 110600.00000 | 153.71082 | 99.65270  | 27.59526 | 28.71557 | 29.53965 | 21.22518 | 1.39173 | -0.31166 |
| 265 | 0.00025 | 110766.66667 | 152.18798 | 98.56673  | 27.57512 | 28.71467 | 29.51862 | 21.20415 | 1.39212 | -0.31434 |
| 266 | 0.00024 | 110766.66667 | 150.41498 | 97.29596  | 27.55163 | 28.71369 | 29.49408 | 21.17960 | 1.39257 | -0.31790 |
| 267 | 0.00024 | 111066.66667 | 149.03836 | 96.30441  | 27.53335 | 28.71297 | 29.47497 | 21.16050 | 1.39292 | -0.31944 |
| 268 | 0.00024 | 111400.00000 | 147.68387 | 95.32451  | 27.51535 | 28.71230 | 29.45614 | 21.14166 | 1.39327 | -0.32258 |
| 269 | 0.00023 | 111733.33333 | 146.29991 | 94.31879  | 27.49692 | 28.71165 | 29.43685 | 21.12237 | 1.39363 | -0.32689 |
| 270 | 0.00023 | 112066.66667 | 144.89880 | 93.29584  | 27.47823 | 28.71103 | 29.41727 | 21.10280 | 1.39400 | -0.32899 |
| 271 | 0.00023 | 112400.00000 | 143.48049 | 92.25532  | 27.45929 | 28.71044 | 29.39740 | 21.08293 | 1.39437 | -0.33109 |
| 272 | 0.00023 | 112566.66667 | 141.82237 | 91.03228  | 27.43710 | 28.70980 | 29.37411 | 21.05964 | 1.39481 | -0.33520 |
| 273 | 0.00022 | 113033.33333 | 140.52538 | 90.07053  | 27.41971 | 28.70934 | 29.35584 | 21.04137 | 1.39515 | -0.33727 |
| 274 | 0.00022 | 113300.00000 | 138.96121 | 88.90450  | 27.39871 | 28.70883 | 29.33374 | 21.01927 | 1.39556 | -0.33950 |
| 275 | 0.00022 | 113966.66667 | 137.86566 | 88.08369  | 27.38398 | 28.70851 | 29.31822 | 21.00375 | 1.39586 | -0.34204 |
| 276 | 0.00021 | 114300.00000 | 136.33733 | 86.93282  | 27.36340 | 28.70809 | 29.29650 | 20.98203 | 1.39627 | -0.34582 |
| 277 | 0.00021 | 114633.33333 | 134.79135 | 85.76153  | 27.34254 | 28.70772 | 29.27446 | 20.95999 | 1.39668 | -0.34798 |
| 278 | 0.00021 | 115133.33333 | 133.42079 | 84.71695  | 27.32403 | 28.70743 | 29.25486 | 20.94038 | 1.39705 | -0.35039 |
| 279 | 0.00020 | 115266.66667 | 131.60813 | 83.32614  | 27.29949 | 28.70711 | 29.22882 | 20.91435 | 1.39755 | -0.35251 |
| 280 | 0.00020 | 115400.00000 | 129.79091 | 81.92082  | 27.27484 | 28.70685 | 29.20260 | 20.88813 | 1.39805 | -0.35292 |
| 281 | 0.00020 | 115566.66667 | 127.99961 | 80.52427  | 27.25049 | 28.70666 | 29.17663 | 20.86216 | 1.39854 | -0.35453 |
| 282 | 0.00020 | 115566.66667 | 126.01442 | 78.96286  | 27.22345 | 28.70654 | 29.14769 | 20.83322 | 1.39910 | -0.35595 |
| 283 | 0.00019 | 115566.66667 | 124.02923 | 77.38633  | 27.19635 | 28.70649 | 29.11858 | 20.80411 | 1.39966 | -0.35595 |
| 284 | 0.00019 | 115900.00000 | 122.38960 | 76.07224  | 27.17392 | 28.70651 | 29.09440 | 20.77992 | 1.40012 | -0.35762 |
| 285 | 0.00019 | 115900.00000 | 120.39868 | 74.46133  | 27.14663 | 28.70662 | 29.06485 | 20.75038 | 1.40069 | -0.35697 |
| 286 | 0.00018 | 116066.66667 | 118.57157 | 72.96744  | 27.12153 | 28.70679 | 29.03755 | 20.72308 | 1.40122 | -0.35839 |
| 287 | 0.00018 | 116566.66667 | 117.07349 | 71.73093  | 27.10091 | 28.70698 | 29.01503 | 20.70055 | 1.40165 | -0.35942 |
| 288 | 0.00018 | 116566.66667 | 115.07112 | 70.06094  | 27.07330 | 28.70731 | 28.98471 | 20.67024 | 1.40224 | -0.35903 |
| 289 | 0.00017 | 116700.00000 | 113.19808 | 68.48000  | 27.04741 | 28.70770 | 28.95612 | 20.64165 | 1.40280 | -0.35923 |
| 290 | 0.00017 | 116700.00000 | 111.19343 | 66.76657  | 27.01964 | 28.70819 | 28.92525 | 20.61078 | 1.40340 | -0.35944 |
| 291 | 0.00017 | 116866.66667 | 109.35123 | 65.17131  | 26.99407 | 28.70873 | 28.89663 | 20.58216 | 1.40397 | -0.35852 |
| 292 | 0.00016 | 116866.66667 | 107.35022 | 63.41467  | 26.96623 | 28.70939 | 28.86524 | 20.55077 | 1.40458 | -0.35878 |
| 293 | 0.00016 | 116866.66667 | 105.35574 | 61.63738  | 26.93842 | 28.71014 | 28.83361 | 20.51914 | 1.40521 | -0.35761 |
| 294 | 0.00016 | 116533.33333 | 103.07944 | 59.57447  | 26.90661 | 28.71110 | 28.79706 | 20.48259 | 1.40593 | -0.35477 |
| 295 | 0.00016 | 116400.00000 | 100.98796 | 57.64418  | 26.87731 | 28.71208 | 28.76303 | 20.44856 | 1.40660 | -0.35406 |
| 296 | 0.00015 | 116233.33333 | 98.87914  | 55.66136  | 26.84769 | 28.71317 | 28.72823 | 20.41376 | 1.40730 | -0.35244 |
| 297 | 0.00015 | 116233.33333 | 96.92787  | 53.79150  | 26.82022 | 28.71426 | 28.69556 | 20.38109 | 1.40795 | -0.34986 |
| 298 | 0.00015 | 116400.00000 | 95.11929  | 52.02587  | 26.79471 | 28.71535 | 28.66485 | 20.35038 | 1.40857 | -0.34895 |
| 299 | 0.00014 | 116400.00000 | 93.18470  | 50.09999  | 26.76736 | 28.71660 | 28.63149 | 20.31702 | 1.40924 | -0.34687 |
| 300 | 0.00014 | 116233.33333 | 91.13243  | 48.01154  | 26.73829 | 28.71801 | 28.59549 | 20.28102 | 1.40996 | -0.34430 |
| 301 | 0.00014 | 116233.33333 | 89.22006  | 46.01989  | 26.71113 | 28.71942 | 28.56132 | 20.24684 | 1.41066 | -0.34289 |
| 302 | 0.00013 | 116066.66667 | 87.19545  | 43.85927  | 26.68232 | 28.72099 | 28.52442 | 20.20995 | 1.41140 | -0.34032 |
| 303 | 0.00013 | 116066.66667 | 85.31819  | 41.80391  | 26.65555 | 28.72254 | 28.48948 | 20.17501 | 1.41212 | -0.33659 |
| 304 | 0.00013 | 115900.00000 | 83.32757  | 39.56487  | 26.62709 | 28.72427 | 28.45161 | 20.13714 | 1.41289 | -0.33519 |
| 305 | 0.00013 | 115566.66667 | 81.24453  | 37.15002  | 26.59725 | 28.72617 | 28.41097 | 20.09650 | 1.41373 | -0.33100 |
| 306 | 0.00012 | 115566.66667 | 79.42048  | 34.96931  | 26.57106 | 28.72792 | 28.37445 | 20.05998 | 1.41448 | -0.32705 |

|     |         |              |          |            |          |          |          |          |         |          |
|-----|---------|--------------|----------|------------|----------|----------|----------|----------|---------|----------|
| 307 | 0.00012 | 115266.66667 | 77.40785 | 32.48444   | 26.54211 | 28.72994 | 28.33304 | 20.01857 | 1.41534 | -0.32432 |
| 308 | 0.00012 | 115266.66667 | 75.62067 | 30.20201   | 26.51634 | 28.73182 | 28.29519 | 19.98072 | 1.41612 | -0.32044 |
| 309 | 0.00011 | 114933.33333 | 73.63921 | 27.57944   | 26.48771 | 28.73398 | 28.25192 | 19.93744 | 1.41703 | -0.31653 |
| 310 | 0.00011 | 114766.66667 | 71.79141 | 25.03765   | 26.46095 | 28.73609 | 28.21018 | 19.89571 | 1.41790 | -0.31239 |
| 311 | 0.00011 | 114766.66667 | 70.06319 | 22.56767   | 26.43587 | 28.73813 | 28.16981 | 19.85534 | 1.41875 | -0.30987 |
| 312 | 0.00011 | 114600.00000 | 68.26769 | 19.89683   | 26.40977 | 28.74032 | 28.12636 | 19.81188 | 1.41967 | -0.30391 |
| 313 | 0.00010 | 114466.66667 | 66.50926 | 17.16684   | 26.38415 | 28.74254 | 28.08215 | 19.76768 | 1.42061 | -0.30122 |
| 314 | 0.00010 | 114133.33333 | 64.66692 | 14.17190   | 26.35726 | 28.74495 | 28.03388 | 19.71940 | 1.42164 | -0.29604 |
| 315 | 0.00010 | 113966.66667 | 62.95166 | 11.24577   | 26.33217 | 28.74727 | 27.98693 | 19.67246 | 1.42265 | -0.29083 |
| 316 | 0.00010 | 113800.00000 | 61.26018 | 8.21530    | 26.30739 | 28.74962 | 27.93852 | 19.62405 | 1.42369 | -0.28699 |
| 317 | 0.00009 | 113333.33333 | 59.44139 | 4.77739    | 26.28068 | 28.75223 | 27.88385 | 19.56937 | 1.42487 | -0.28165 |
| 318 | 0.00009 | 113166.66667 | 57.81396 | 1.52494    | 26.25674 | 28.75463 | 27.83235 | 19.51787 | 1.42599 | -0.27633 |
| 319 | 0.00009 | 113166.66667 | 56.29918 | -1.66951   | 26.23442 | 28.75692 | 27.78196 | 19.46749 | 1.42710 | -0.27160 |
| 320 | 0.00009 | 112866.66667 | 54.67065 | -5.30463   | 26.21038 | 28.75945 | 27.72484 | 19.41037 | 1.42835 | -0.26559 |
| 321 | 0.00008 | 112366.66667 | 52.98079 | -9.32344   | 26.18539 | 28.76214 | 27.66194 | 19.34747 | 1.42974 | -0.26014 |
| 322 | 0.00008 | 112200.00000 | 51.48172 | -13.12535  | 26.16317 | 28.76459 | 27.60265 | 19.28818 | 1.43107 | -0.25488 |
| 323 | 0.00008 | 112066.66667 | 50.02674 | -17.05488  | 26.14158 | 28.76701 | 27.54158 | 19.22711 | 1.43243 | -0.25006 |
| 324 | 0.00008 | 111733.33333 | 48.52568 | -21.38660  | 26.11927 | 28.76957 | 27.47447 | 19.16000 | 1.43395 | -0.24282 |
| 325 | 0.00008 | 111566.66667 | 47.12794 | -25.70526  | 26.09846 | 28.77201 | 27.40778 | 19.09330 | 1.43547 | -0.23781 |
| 326 | 0.00007 | 111400.00000 | 45.75901 | -30.23484  | 26.07804 | 28.77444 | 27.33802 | 19.02355 | 1.43706 | -0.23300 |
| 327 | 0.00007 | 111066.66667 | 44.36462 | -35.19240  | 26.05721 | 28.77696 | 27.26188 | 18.94740 | 1.43882 | -0.22580 |
| 328 | 0.00007 | 111066.66667 | 43.13812 | -39.87553  | 26.03887 | 28.77922 | 27.19013 | 18.87566 | 1.44049 | -0.21991 |
| 329 | 0.00007 | 111233.33333 | 42.00553 | -44.50039  | 26.02191 | 28.78135 | 27.11943 | 18.80495 | 1.44214 | -0.21452 |
| 330 | 0.00007 | 111066.66667 | 40.77803 | -49.87700  | 26.00350 | 28.78368 | 27.03740 | 18.72293 | 1.44408 | -0.20896 |
| 331 | 0.00006 | 111066.66667 | 39.64445 | -55.21874  | 25.98648 | 28.78587 | 26.95607 | 18.64160 | 1.44602 | -0.20325 |
| 332 | 0.00006 | 111066.66667 | 38.54803 | -60.77087  | 25.96999 | 28.78802 | 26.87168 | 18.55721 | 1.44805 | -0.19659 |
| 333 | 0.00006 | 111066.66667 | 37.48259 | -66.57243  | 25.95395 | 28.79014 | 26.78365 | 18.46918 | 1.45018 | -0.19103 |
| 334 | 0.00006 | 111066.66667 | 36.45431 | -72.59618  | 25.93845 | 28.79222 | 26.69239 | 18.37792 | 1.45242 | -0.18437 |
| 335 | 0.00006 | 111566.66667 | 35.61663 | -77.84588  | 25.92582 | 28.79392 | 26.61296 | 18.29849 | 1.45438 | -0.17922 |
| 336 | 0.00006 | 112066.66667 | 34.81371 | -83.19607  | 25.91369 | 28.79558 | 26.53210 | 18.21763 | 1.45640 | -0.17220 |
| 337 | 0.00005 | 112533.33333 | 34.01725 | -88.84090  | 25.90165 | 28.79724 | 26.44687 | 18.13240 | 1.45854 | -0.16845 |
| 338 | 0.00005 | 113033.33333 | 33.26690 | -94.49576  | 25.89030 | 28.79881 | 26.36157 | 18.04710 | 1.46071 | -0.16128 |
| 339 | 0.00005 | 113633.33333 | 32.57524 | -100.02462 | 25.87983 | 28.80028 | 26.27825 | 17.96377 | 1.46285 | -0.15527 |
| 340 | 0.00005 | 114466.66667 | 31.97143 | -105.12057 | 25.87069 | 28.80157 | 26.20150 | 17.88703 | 1.46483 | -0.15055 |
| 341 | 0.00005 | 115266.66667 | 31.39129 | -110.27234 | 25.86189 | 28.80281 | 26.12397 | 17.80949 | 1.46686 | -0.14358 |
| 342 | 0.00005 | 116233.33333 | 30.88312 | -115.00593 | 25.85418 | 28.80392 | 26.05276 | 17.73829 | 1.46873 | -0.13774 |
| 343 | 0.00005 | 117000.00000 | 30.34293 | -120.28028 | 25.84598 | 28.80509 | 25.97347 | 17.65900 | 1.47083 | -0.13294 |
| 344 | 0.00005 | 117833.33333 | 29.86243 | -125.19629 | 25.83869 | 28.80615 | 25.89960 | 17.58513 | 1.47281 | -0.12446 |
| 345 | 0.00004 | 118633.33333 | 29.39691 | -130.17431 | 25.83161 | 28.80717 | 25.82484 | 17.51037 | 1.47483 | -0.11942 |
| 346 | 0.00004 | 119766.66667 | 29.04318 | -134.10710 | 25.82623 | 28.80796 | 25.76579 | 17.45132 | 1.47644 | -0.11324 |
| 347 | 0.00004 | 120733.33333 | 28.68504 | -138.22826 | 25.82079 | 28.80875 | 25.70394 | 17.38947 | 1.47813 | -0.10582 |
| 348 | 0.00004 | 121666.66667 | 28.35716 | -142.13029 | 25.81580 | 28.80948 | 25.64539 | 17.33092 | 1.47975 | -0.09817 |
| 349 | 0.00004 | 122633.33333 | 28.06265 | -145.74507 | 25.81132 | 28.81014 | 25.59117 | 17.27670 | 1.48125 | -0.09283 |
| 350 | 0.00004 | 123300.00000 | 27.74072 | -149.82120 | 25.80642 | 28.81087 | 25.53005 | 17.21557 | 1.48296 | -0.08485 |
| 351 | 0.00004 | 123900.00000 | 27.44728 | -153.65491 | 25.80195 | 28.81153 | 25.47257 | 17.15810 | 1.48458 | -0.07663 |
| 352 | 0.00004 | 124733.33333 | 27.24231 | -156.40241 | 25.79883 | 28.81199 | 25.43139 | 17.11692 | 1.48575 | -0.06962 |
| 353 | 0.00004 | 125233.33333 | 27.00927 | -159.59838 | 25.79527 | 28.81252 | 25.38349 | 17.06902 | 1.48711 | -0.06124 |
| 354 | 0.00004 | 125700.00000 | 26.80846 | -162.41584 | 25.79221 | 28.81298 | 25.34127 | 17.02680 | 1.48832 | -0.05395 |
| 355 | 0.00004 | 126000.00000 | 26.61946 | -165.12306 | 25.78933 | 28.81341 | 25.30071 | 16.98624 | 1.48948 | -0.04531 |
| 356 | 0.00004 | 126300.00000 | 26.47152 | -167.28066 | 25.78708 | 28.81375 | 25.26839 | 16.95392 | 1.49042 | -0.03785 |
| 357 | 0.00004 | 126633.33333 | 26.37894 | -168.64838 | 25.78567 | 28.81396 | 25.24791 | 16.93343 | 1.49101 | -0.02909 |
| 358 | 0.00004 | 127133.33333 | 26.36965 | -168.78644 | 25.78552 | 28.81398 | 25.24584 | 16.93137 | 1.49107 | -0.02030 |

|     |         |              |          |            |          |          |          |          |         |          |
|-----|---------|--------------|----------|------------|----------|----------|----------|----------|---------|----------|
| 359 | 0.00004 | 127633.33333 | 26.40217 | -168.30388 | 25.78602 | 28.81391 | 25.25307 | 16.93859 | 1.49086 | -0.01274 |
|-----|---------|--------------|----------|------------|----------|----------|----------|----------|---------|----------|

## 7 References

- Andersson, L. E. (2002). *An Analytical Model for Cylinder Pressure in a Four Stroke SI Engine*. Warrendale: SAE.
- Bernardo Ribeiro, J. M. (2006). *Otto and VCR Miller Engine Performance during the European Driving Cycle*. Warrendale: SAE.
- Colin R Ferguson, A. T. (2001). Internal Combustion Engines. In A. T. Colin R Ferguson, *Internal Combustion Engines* (p. 256). New York: John Wiley & Sons, Inc.
- H. Fujimoto, H. Y. (2011). *A Study on Improvement of Indicated Thermal Efficiency of ICE using High Compression Ratio and Reduction of Cooling Loss*. Warrendale: SAE.
- Hall, N. (2015, 005 05). *Specific Heats*. Retrieved from NASA: <https://www.grc.nasa.gov/www/k-12/airplane/specheat.html>
- Helmenstine, A. M. (2017, 08 16). *The Chemical Composition of Air*. Retrieved from Thought Co: <https://www.thoughtco.com/chemical-composition-of-air-604288>
- Heywood, J. B. (1988). *Internal Combustion Engine Fundamentals* (15th ed.). New Dehli: McGraw Hill Education (India) Private Limited.
- J.Sureshkumar, G. a. (2015). *Study on Effect of Engine Operating Parameters on Flame Characteristics*. Warrendale: SAE.
- K. Nakata, S. D. (2015). *Engine Technologies for achieving 45% Thermal Efficiency*. Warrendale: SAE.
- Lambda Power. (2018, 02 21). *Tech Notes*. Retrieved from Lambda Power: <https://secure.lambdapower.co.uk/TechNotes/Tech-5.asp>
- Lumley, J. L. (1999). *Engines an Introduction* (6th ed.). New York: Cambridge University Press.
- M Mitta, G. Z. (2008). *Fast Mass Fraction Burned calculation using the net pressure method for real time applications*. Michigan: Michigan State University.
- M. Mostafavi, B. A. (n.d.). *Thermodynamic Analysis of Turbocharged Spark Ignition Engine (Otto Cycle) - Part 1 - Heat Energy Available in the Exhaust Gases*. Warrendale: SAE.
- Martins, B. R. (2007). *Direct Comparison of an Engine Working under Otto, Miller and Diesel Cycles: Thermodynamic Analysis and Real Engine Performance*. Warrendale: SAE.

- Mehrdad Ehsani, Y. G. (2010). *Modern Electric, Hybrid Electric and Fuel Cell Vehicles- Fundamentals, Theory and Design - Second Edition*. Boca Raton: Taylor and Francis Group.
- Nuclear Power. (2018, 04 13). *Otto Cycle - Otto Engine*. Retrieved from Nuclear Power: <https://www.nuclear-power.net/nuclear-engineering/thermodynamics/thermodynamic-cycles/otto-cycle-otto-engine/>
- Nuclear Power. (2018, 04 20). *Thermal Efficiency*. Retrieved from Nuclear Power: <https://www.nuclear-power.net/nuclear-engineering/thermodynamics/laws-of-thermodynamics/thermal-efficiency/>
- Perkins, C. (2017, 09 21). *Mercedes-AMGs F1 can make more power than waste energy*. Retrieved from Road and Track: <https://www.roadandtrack.com/motorsports/a12443313/mercedes-amgs-f1-engine-is-amazingly-efficient/>
- Randolph, D. A. (2018, 03/04). Count your Losses. *Race Engine Technology*, pp. 42-53.
- Robert Bosch. (2011). *Automotive Handbook (8th Edition)*. Chichester: John Wiley and Sons Ltd.
- Rockett Brand Racing Fuel. (2018, 04 21). *Fast Burn or Slow Burn Gasoline - Which is better?* Retrieved from Rockett Brand: [http://www.rockettbrand.com/downloads/tech\\_bulletins/Tech-Fast%20Burn%20Or%20Slow%20Burn.pdf](http://www.rockettbrand.com/downloads/tech_bulletins/Tech-Fast%20Burn%20Or%20Slow%20Burn.pdf)
- Rodgers, D. (2014, 05 10). *Combustion Pressure measurement for efficient Engine Diagnostics*. Retrieved from Autoelex: <http://autoelexblog.blogspot.co.uk/2014/05/combustion-pressure-measurement-for.html>
- Sankararaj, S. (2018, 04 20). *Otto Cycle - Processes with P-V and T-S Diagrams*. Retrieved from Mechteacher.com: <http://mechteacher.com/otto-cycle/>
- Sparknotes. (2018, 04 13). *Enthalpy*. Retrieved from Sparknotes: <http://www.sparknotes.com/testprep/books/sat2/chemistry/chapter9section1.rhtml>
- Stone, R. (1992). *Introduction to Internal Combustion Engines - 2nd Edition*. Basingstoke: The Macmillan Press Ltd.
- Suryawanshi, S. C. (2015). *Gasoline Direct Injection: An Efficient Technology*. Mumbai: Elsevier.
- Taylor, C. F. (1985). *The Internal Combustion Engine in Theory and Practice, Volume 1: Thermodynamics, Fluid Flow, Performance 2nd Edition*. Massachusetts: The MIT Press.

Turns, S. R. (2006). *Thermodynamics*. Cambridge: Cambridge University Press.

Urieli, I. (2018, 04 20). *Chapter 3: The First Law of Thermodynamics for Closed Systems*. Retrieved from Ohio: [https://www.ohio.edu/mechanical/thermo/Intro/Chapt.1\\_6/Chapter3d.html](https://www.ohio.edu/mechanical/thermo/Intro/Chapt.1_6/Chapter3d.html)

X-Engineer. (2018, 04 14). *Air-Fuel Ratio, Lambda and Engine Performance*. Retrieved from X-Engineer: <https://x-engineer.org/automotive-engineering/internal-combustion-engines/performance/air-fuel-ratio-lambda-engine-performance/>

X-Engineer. (2018, 04 19). *Mechanical Efficiency and Friction mean effective pressure (FMEP)*. Retrieved from X-Engineer: <https://x-engineer.org/automotive-engineering/internal-combustion-engines/performance/mechanical-efficiency-friction-mean-effective-pressure-fmep/>

Yamamoto, H. (1999). *Investigation on Relationship between Thermal Efficiency and NO<sub>x</sub> Formation in Ultra-Lean Combustion*. Warrendale: SAE.

Yamamoto, H. (1999). *Investigation on Relationship Between Thermal Efficiency and NO<sub>x</sub> Formation is Ultra-Lean Combustion*. Warrendale: SAE.