DEVELOPING CENTRIFUGAL COMPRESSOR PERFORMANCE PREDICTING TOOL FOR HEALTH MONITORING

By

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CERTIFICATION OF APPROVAL

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ABSTRACT

The aim of this project is to develop predicting tool for centrifugal compressor performance in petrochemical industry. The predicting tool was developed as part of predictive maintenance strategy in assisting maintenance monitoring of the equipment. It is important for a production plant to maintain the performance of centrifugal compressor because performance deterioration has significant impact in their production especially profit of a company that depends on continuous operation. Thus, centrifugal compressor model was developed using thermodynamics principle which is the Schultz Polytropic Analysis. The predicting tool was developed by using Microsoft Excel and Visual Basic Application for Graphical User Interface (GUI). Microsoft Excel is used because it is cheaper compared to other software and users can change the source code anytime they wish to. In order to analyze a centrifugal compressor, historical data of low pressure and high pressure centrifugal compressor from PETRONAS Carigali, Kerteh were used for performance analysis. The tool developed is able to give the compressor polytropic head, efficiency and gas power for given input conditions.. Based on the results obtained, both compressors are operating at optimum condition but the efficiency of high pressure compressor is lower compared to low pressure compressor. Therefore, this tool can assist plant operators to monitor the performance of centrifugal compressor which is useful information for predicting maintenance.

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LIST OF ABBREVIATIONS

ASME PTC 10	American Society of Mechanical Engineers Performance Technical Code 10
GUI	Graphical User Interface
HP Compressor	High Pressure Compressor
LP Compressor	Low Pressure Compressor
OEM	Original Equipment Manufacturer
PETRONAS	Petroliam Nasional Berhad
UTP	Universiti Teknologi PETRONAS
VBA	Visual basic Application

CHAPTER 1

INTRODUCTION

1.1 Background

Centrifugal compressor is widely used in industry such as power generation, automotive, production and petrochemical plants. Typical function of a centrifugal compressor is to compress gas or air to higher pressure. Breakdown and deterioration in performance of centrifugal compressor can have negative impact on the operation and profit of a company or business that depends on continuous production. (Padmanabhan, n.d.). Therefore, maintenance is important routine in an operation to maintain the functional requirement of the equipment. Maintenance can be divided into several categories, which are Reactive Maintenance, Preventive Maintenance and Predictive Maintenance.

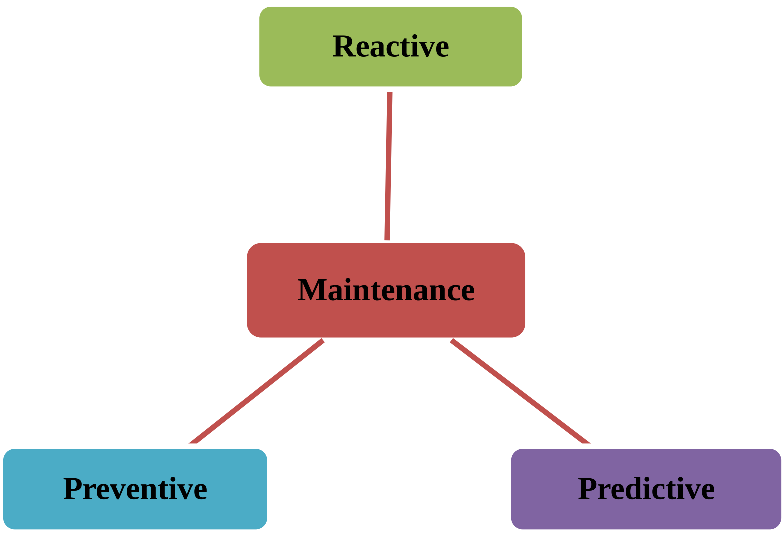

Figure 1.1 Types of Maintenance

Reactive Maintenance is defined as run to failure or breakdown maintenance in which the repair work is only done after failure has occurred rather than taking any preemptive action. A philosophy to describe this type of maintenance is *"just let it break."* Preventive maintenance on the other hand is a periodic and routine maintenance regardless of the equipment condition. Usually, schedule of maintenance is based on past experience or Original Equipment Manufacturer (OEM) recommendation. Preventive maintenance is also known as *"fix it before it breaks."* Predictive maintenance on the other hand is condition monitoring where maintenance is done based on the equipment condition. This maintenance is set by the rule of *"if it isn't broke, don't fix it."* Advantages of this maintenance are able to avoid unexpected catastrophic breakdowns with expensive or dangerous consequences, reduce number or overhauls, eliminate unnecessary intervention with the consequent risk of introducing faults on smoothly operating machine, allow spare parts to be ordered in time with overseen possible failure, and avoid intervention time since overhaul can be scheduled when convenient.

This project applies predictive maintenance to monitor the performance of centrifugal compressor in petrochemical industries where condition monitoring is used by applying thermodynamics principle. This method collects data of a centrifugal compressor to analyze the performance of the compressor for health monitoring.

1.2 Problem Statement

Petrochemical industry is an industry that deals with chemical products derived from petroleum. A petrochemical plant usually consists of facilities for material processing which includes rotating equipment in its operation. In petrochemical plants, rotating equipments deterioration can affect the entire production process and this costs huge money. In order to overcome this, it is common nowadays for a plant to install performance monitoring tool for health monitoring purpose. This is a very powerful tool to identify the equipment health conditions. However, they are provided by manufacturers and there are still equipments that do not have performance monitoring tool. Thus, this study embarks to develop centrifugal compressor performance predicting tool for health monitoring purpose.

1.3 Objectives

This project has several objectives, which are:

i. To model a centrifugal compressor using thermodynamics principles
ii. To develop performance analysis tool for health monitoring of a centrifugal compressor

1.4 Scope of Study

The scope of study of this project involves centrifugal compressor as rotating equipment in petrochemical plants. The health monitoring is done by evaluating the performance of the compressor as compared to its designed performance. The analysis is done based on thermodynamics principle and calculation. In this case, the model is developed for steady state condition. Under the steady state condition, the flow process is characterized by the assumption that no properties within the control volume, at the boundaries and the heat and work interaction between a steady flow system and its surroundings do not change with time.

CHAPTER 2
LITERATURE REVIEW

2.1 Compressor

A compressor is capable of compressing gas or air to very high pressures (Cengel and Boles, 2011). Compressor can be divided into two type, positive displacement and negative displacement. The positive displacement compressors raise potential energy of the fluid by reducing its volume and thus, increasing pressure. The dynamic compressor on the other hand works mainly by spinning its impeller(s) to accelerate the velocity of working fluid. High velocity of fluid will increase in kinetic energy and is then converted to potential energy. Compressors are similar to pumps whereby both increase the pressure of the fluid and transport the fluid through a pipe (Davidson and von Bertele, 1996). The following figure shows types of compressor:

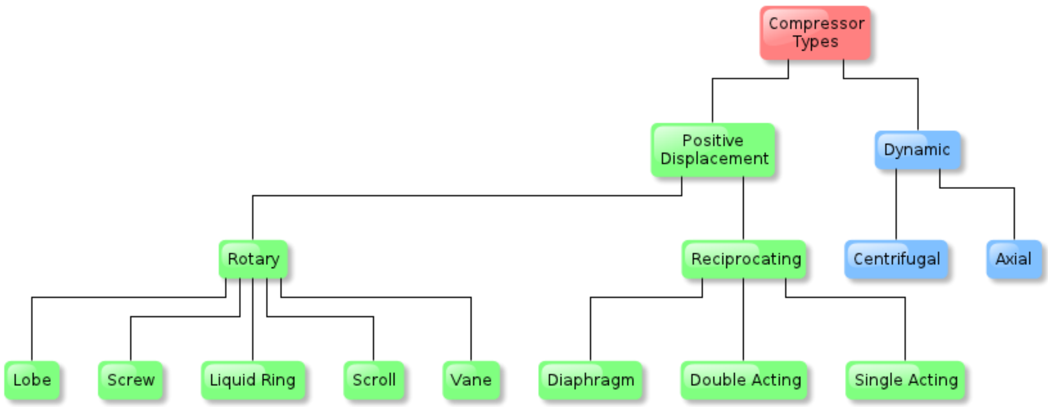

Figure 2.1 Type of Compressor (Source: Wikipedia: Gas Compressor)

2.1.1 Centrifugal Compressor

Centrifugal compressor uses a rotating disk or impeller in a shaped housing to force the gas to the rim of the impeller, which increases the gas velocity. A diffuser (divergent duct) section converts the velocity energy to pressure energy. This type of compressor is commonly used for continuous and stationary service in industries such as oil refineries, chemical and petrochemical plants and natural gas processing plants. Their application can be from 100 horsepower (75 kW) to thousands of horsepower. With multiple staging, they can achieve high output pressures of greater than 10 000 psi (69 MPa).

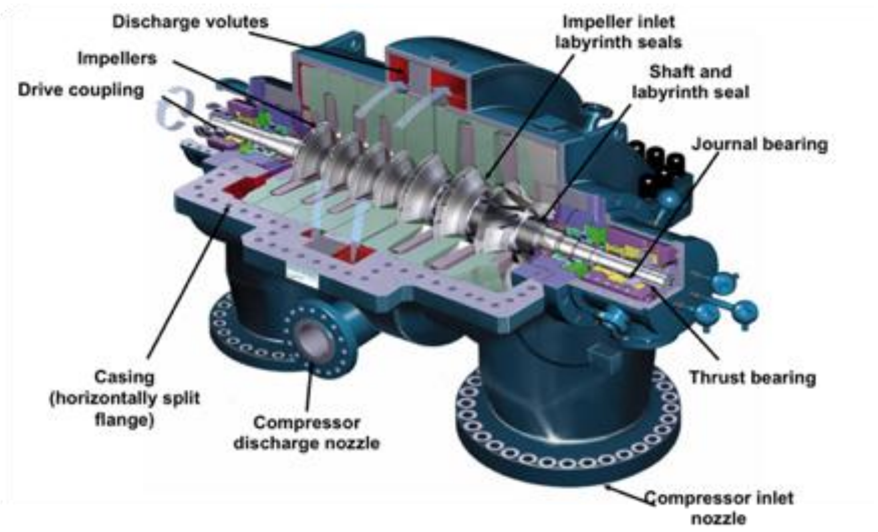

Figure 2.2 Centrifugal Compressor (Source: PETRONAS Training Materials)

According to Rasmussen and Kurz (2009), gas enters the inlet nozzle of the compressor, which is then guided to the inlet of the first impeller. An impeller consists of rotating vanes and when the gas is forced through the impeller by rapidly rotating impeller blades, it will impart mechanical energy to the gas. The velocity of the gas leaving the impeller increases, so as the static pressure. While the gas is in the diffuser, part of the velocity is converted into static pressure. Diffusers in the compressor can be vaneless or made of several numbers of vanes, which are tangential to the impeller. For a compressor with multiple stage or more than one impeller, gas discharged from the first stage will be again brought into the next impeller through the return channel and return vanes. Once the gas enters the diffuser of the last impeller, it will be directed to the discharge system. The discharge system can either make use of a volute to further convert velocity into static pressure or just collect the gas before it exits the compressor through discharge nozzle.

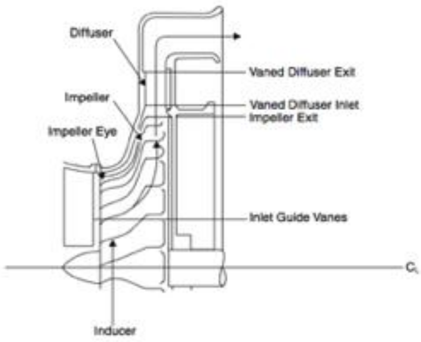

Figure 2.3 Impeller of A Centrifugal Compressor *(Source: Gas Turbine Handbook)*

2.2 Performance Degradation in Centrifugal Compressor

The performance of centrifugal compressor used in the process industries deteriorates due to several factors which result in its performance maps (Salamat, 2012). There are many factors that contribute to performance degradation of a compressor such as compressor fouling, blade tip ribs, vibrations in the shaft as indicator of rotor problems, tip seal and labyrinth wear & damage, erosion and corrosion. Compressor degradation can be divided into two, recoverable and non recoverable. Non recoverable performance deterioration is associated with widening clearances between moving and stationary parts of the compressor in which, the damage requires replacement. As for recoverable performance deterioration, it is related to the light maintenance such as cleaning and washing. An example for recoverable performance deterioration is fouling, which is the most common factor of compressor deterioration. Therefore, this paper discusses more on fouling since the performance deterioration is recoverable and can be detected earlier by performance monitoring in which the scope of study is by using thermodynamics principle.

Fouling in compressor refers to solid substances, usually polymers, which adhere to the internal aerodynamic surfaces of the compressors. Fouling usually will not cause catastrophic failure, but can gradually reduce the efficiency of the compressors or in some worse cases, block the flow path and stop the production (Wang et al., 2003). Similarly, Hanlon (2001) in his book mentioned that dirt or polymer buildup on the impeller or diaphragm surfaces will cause uneven surfaces and in some cases, it may restrict the diffuser passage which in turn reduced overall efficiency. Furthermore, Hanlon (2001), Wang et al (2003) and Bloch (2006) discussed that the probability of polymerization in petrochemical industry is high in conditions where process gas temperature is above 90°C (194°F) and higher pressure. On top of that, fouling also depends on the surface finish and gas composition in which fouling is proportional to concentration of reactable hydrocarbons in the process gas.

Having solid substances deposited on the impellers, fouling can restricts flow and increases boundary layer thickness, which in turn increases frictional losses. According to Forsthoffer (2005), forces exerted on the foulant may cause it to chip off with time as it becomes dry and brittle which eventually results change in rotor balance and performance (head and efficiency). Bloch (2006) in his book mentioned that fouling affects efficiency through three basic loss mechanisms as follows:

i. Friction loss
ii. Flow area reduction
iii. Random changes of pressure distribution on blade

Meher-Homji and Bromly (2004) in their article on the other hand discussed that certain factors can be used to indicate fouling in compressor such as:

i. Drop in compressor mass flow rate on fixed geometry engines
ii. Drop in compressor efficiency and high pressure ratio (or discharge pressure)

Snider (2006) in his article also revealed that fouling can affects labyrinth seals between the wheels where stage efficiency may be reduced. Labyrinth seals which prevent gas from leaking from a higher pressure wheel to lower pressure wheel are made up of teeth that create turbulence and resistance to slow down the gas. When the teeth are fouled or damaged, there is less resistance which will increase gas leakage.

2.3 Health Monitoring by Condition Monitoring

A gas compressor has a few measurable parameters such as suction temperature and suction pressure. Nevertheless, it is difficult to analyze these data as the interpretation from the related data is inconsistent (Jasmani et al., 2012). For example, an increase in discharged pressure, unaffected discharged temperature, decrease in transverse aft vibration and decrease in suction temperature does not provide any useful information when analyzed. Therefore, performance indicator approach is more suitable when analyzing parameters for gas compressors. Gresh (2001) and Forsthoffer (2005) in their book also pointed out that performance deterioration monitoring can be done by condition monitoring where the performance curve of a compressor is used for monitoring mechanism. In this case, data trending is developed and compared where performance deterioration in compressor will cause the performance curve to shift downward and toward reduced flow.

Some of the parameters in performance curve of a compressor include polytropic head, polytropic efficiency and gas power. Polytropic head is the reversible work required to compress a unit mass of gas by a polytropic process from the inlet total pressure and temperature to the discharge total pressure and temperature (Gresh, 2001). The polytropic head is expressed in J/mol and is determined from the suction and discharge pressure and temperature, assuming the gas composition is known. The parameters are related as shown in equation 2.1:

$$H_{poly} = \left(\frac{n}{n-1}\right)(ZRT_1)\left[\left(\frac{P_2}{P_1}\right)^{\frac{n-1}{n}} - 1\right] \quad (2.1)$$

where H_{poly} is polytropic head, n is polytropic exponent, Z is average compressibility factor, R is gas constant in J/mol.K, T_1 is suction temperature, P_2 is discharge pressure in bar and P_1 is suction pressure in bar.

On the other hand, ratio of work output of the system (head) to the work input to the system (shaft power) is defined as efficiency of a thermodynamic system. The difference of head and work is related to the amount of internal losses in the machine due to friction and windage. These losses are indicated by heat which eventually is added to the discharge temperature. Polytropic efficiency is expressed in equation 2.2:

$$\eta_p = \frac{k-1}{k} \frac{\ln\left(\frac{p_2}{p_1}\right)}{\ln\left(\frac{T_2}{T_1}\right)} \quad (2.2)$$

where η_{poly} is polytropic efficiency, T_1 is suction temperature in Kelvin, T_2 is discharge temperature in Kelvin, P_1 is suction pressure in bar, P_2 is discharge pressure in bar and k is specific heat ratio.

On top of that, gas power is defined as energy required to compress a volume of gas to a specified discharged temperature and temperature as shown in equation 2.3:

$$Power_{gas} = \frac{H_{poly}.\dot{M}}{\eta_{poly}} \quad (2.3)$$

where $Power_{gas}$ is gas power in kW, H_{poly} is polytropic head, $\dot{M}$ is mass flow rate in kg/s and η_{poly} is polytropic efficiency. Jasmani et al. in their article mentioned that fouling in compressor could be detected by increased in gas power since fouling in compressor cause the compression process to consume more power than it should.

2.4 Recovering Centrifugal Compressor Performance

Over the years, various methods of preserving compressor performance are developed and practiced by industries that operate compressor in their operation and production. According to Wang et al (2003), petrochemical companies often shutdown their units for cleaning of foul in compressor to restore its efficiency in the early days. As such, methods used to clean out foul in compressor include “nonstick” coating and blade washing where it can be done in offline or online mode. A common practice in plant nowadays is injecting oil or water into the compressor. The reason of injecting oil is that a smooth surface (or wetted with oil) can reduce fouling rate. An analogy to explain this is by taking an example of food will less likely to stick on oiled cookware. However injecting oil can be very expensive and can actually cost an ethylene plant one to two million dollar per year. Therefore, water injection is opted for an alternative to cut down the maintenance cost. Water is injected into the compressor internal to cool down the compressor and helps to minimize fouling in compressor. Hanlon (2001) in his book also suggested preserving compressor performance by wash system that includes water with detergents or hydrocarbons solutions to wet aerodynamic surfaces to prevent polymers attachment. The liquid wash however is limited to 3% of the gas mass flow rate to prevent erosion and should be injected stage by stage with increasing amounts at the discharge.

2.4.1 Blade coating

In the late 1980s or early 1990s, a concept of "nonstick" coating was introduced to the industry (Robichaux, et al., 1995). With the application of nonstick coatings, the fouling problem has tremendously minimized and at certain petrochemical plant where application of coating is practiced, washing practice has been terminated since coating has performed so well. Not only that, there are reports claimed that some ethylene plants have successfully reduce their compressor overhaul frequency which in return saves maintenance cost. Nonetheless, not every plant experiences this success, because there are some plants still experiencing fouling problems even when coating is practiced due to the complexity of petrochemical process.

2.4.2 Offline Washing

Offline washing is usually done with the aid of a detergent where the power recover is effectively achieved. However, Meher Homji and Bromley (2004) in their article mentioned that it is important that compressor washing is practiced with reference to the manufacturer's recommendations for water quality, detergent/water ratio, and other operating procedure. Offline washing can basically clean a dirty compressor and restore power and efficiency where water wash is done with the machine on cranks. Cleaning fluid is usually a mixture of chemical detergent and water depending on type of fouling material found in the compressor and local plant experience. The compressor will then be "soaked" and is later, rinsed with fresh water. Soaking period between each wash and rinse cycle is important to allow the soaping cleaning fluid penetrates through fouling deposition. This will dissolve salts and emulsifying oil or grease components. The advantage of this method is the cleaning process can reach all compressor stages and is most effective when carried out in several steps using soap and water solution followed by rinse cycles using water only.

This method however requires the compressor to shut down and cooling period of 12 to 36 hours depending on the size of operation. Therefore, a plant can lose revenue during shut down

2.4.3 Online Washing

Online washing in compressor is usually aimed to keep a compressor clean for longer period or in other words, simply to avoid problem from developing. This method can extend operating period of a compressor between offline washes by minimizing deposits build up (Meher-Homji, 2004). This method is performed while the unit is in full operation as techniques and wash systems have now developed to the extent that this method can be performed effectively and safely. As such, shutdown period is not required and therefore, the compressor can continue to operate, which helps a company in minimizing loss in revenue. For cleaning fluid, water alone is sometimes used depending on nature of fouling material, but mostly, approved cleaner (detergent) is used to improve effectiveness.

There are two types of cleaning agents, which are “water-based” and solvent-based”. Nowadays, most products contain surfactants, wetting agents, and emulsifier, which involve either an aqueous or petroleum-based solvent system. These products are usually supplied as concentrates and is later diluted with water onsite (typically one part cleaner with four parts water) to produce the cleaning fluid. Originally, solvent-based cleaners have been recognized as the most effective detergent for oil and grease removal, but some of the latest inventions of water-based products formulated are now equally effective. On top of that, water-based products have the advantage of being biodegradable, which is an increasingly important requirement within petrochemical industry.

CHAPTER 3
METHODOLOGY

Condition monitoring is an useful method to detect potential degradation of failure or drop in performance of a centrifugal compressor. It uses realtime or historical data for trending purpose. The first step in methodology of developing the predicting tool involves collecting information on performance deterioration in compressor such as contributing factors and methods of monitoring the performance. Hence, thermodynamics principle is used to model the compressor performance with steady state assumption. In order to analyze the performance of a compressor, historical data of operating conditions of the centrifugal compressor is required. Therefore, historical data and design specification provided by the manufacturer are collected from PETRONAS Carigali, Kertih as collaborating company. The selected compressors are low pressure and high pressure centrifugal compressor of PETRONAS Angsi. Based on the collected data, the predicting tool is developed and actual performance is compared with designed performance.

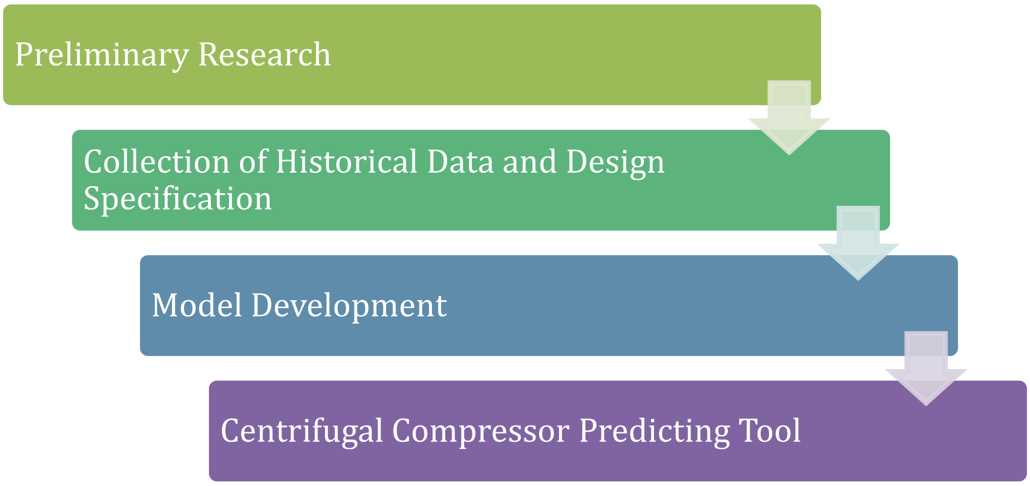

Figure 3.1 Methodology Process

3.1 Gas Analysis

3.1.1 Molar Mass of Gas Mixture

The operating condition of a centrifugal compressor varies with gas composition, therefore, the gas composition compressed by that particular compressor should be analyzed beforehand. For gas analysis calculation, the gas type and mole fraction of each gas type are required from the user. Based on these inputs, the molar mass of the individual gas is first calculated to get the molar mass of the gas mixture. The molar mass of the mixture is calculated as shown in equation 3.1:

$$M_m = \sum y_i M_i \tag{3.1}$$

3.1.2 Gas Constant of Gas Mixture

The gas analysis continued with determining the gas constant of the mixture, which is calculated as shown in equation 3.2 below:

$$R_m = \frac{R_u}{M_m} \tag{3.2}$$

3.1.3 Specific Heat Capacity

In order to calculate the specific heat capacity of the gas mixture, the mass fraction must first be determined. The mass fraction of individual gas is calculated by dividing individual molar mass of gas with molar mass of the mixture using equation 3.3 below:

$$mf_i = \frac{y_i M_i}{M_m} \tag{3.3}$$

The specific heat capacity at constant pressure, c_p is determined by the ideal-gas specific heats as a function of temperature. The specific heat of individual gas, $c_{p,i}$ is first calculated, by equation 3.4 (Cengel and Boles, 2011):

$$\bar{c}_p = a + bT + cT^2 + dT^3 \tag{3.4}$$

At different temperature, the specific heat capacity of the gas will produce different value. Individual specific heat capacity at constant pressure, $c_{p,i}$ will then multiplied by mass fraction. The total of these individual specific heats will produce specific heat capacity at constant pressure of the mixture, $c_{p,m}$. The specific heat at constant pressure, $c_{p,m}$ of the gas mixture is then used to calculate the specific heat at constant volume, $c_{v,m}$ of the mixture as shown in equation 3.5:

$$c_{v,m} = c_{p,m} - R_m \tag{3.5}$$

Finally, the ratio of $c_{p,m}$ and $c_{v,m}$ is calculated as shown in equation 3.6:

$$k = \frac{c_p}{c_v} \tag{4.6}$$

3.2 Polytropic Efficiency

In developing the predicting tool, polytropic efficiency is used for compressor performance evaluation. Polytropic process can describes actual expansion and compression processes of gases, pressure and volume and are related by equation $P = CV^{-n}$. The polytopic efficiency of the compressor is calculated as shown in the equation 3.7:

$$\eta_{poly} = \frac{n-1}{n} \frac{ln\left(\frac{P_2}{P_1}\right)}{ln\left(\frac{T_2}{T_1}\right)} \tag{3.7}$$

3.3 Schultz Polytropic Analysis

The American Society of Mechanical Engineers (ASME) has provided technical documents to conduct test on equipment. For this project, Performance Test Code 10 or also known as ASME PTC 10 is used for polytropic calculation as a reference. The test code implemented the John M. Schultz polytropic procedure for thermodynamic evaluation of a compressor in which the gas may be treated as real gas when the compressibility functions are known. Based on the Schultz method, the arithmetic mean between inlet and discharge conditions shall be used for evaluating compressibility factor, specific heat, X and Y. The curves for Schultz compressibility factor of function X and Y are provided in Appendix A and B respectively. This method is normally used when discharge conditions are unknown and polytropic exponent, n is to be estimated. The definitions of X and Y are shown in equation 3.8 and 3.9:

$$X = \frac{T}{v}\left(\frac{dv}{dT}\right)_P - 1 \tag{3.8}$$

where

$$Y = -\frac{p}{v}\left(\frac{dv}{dp}\right)_T \tag{3.9}$$

3.3.1 Schultz Compressibility Factor

John M. Schultz introduced compressibility functions X and Y in polytropic analysis calculation to supplement the compressibility factor Z for changes in fluid properties. The value of X and Y can be obtained from the graphs in Appendix A and Appendix B. In order to obtain the value of both X and Y, reduced pressure and reduced temperature of the gas mixtures must first be determined. The reduced pressure, P_r and reduced temperature T_r of the mixture are calculated with the following equations:

$$P_r = \frac{P}{P_{cr}} \; where \; P_{cr} = Critical\ Pressure \tag{3.10}$$

and

$$T_r = \frac{T}{T_{cr}} \; where \; T_{cr} = Critical\ Temperature \tag{3.11}$$

However, the critical pressure, P_{cr} and critical temperature, T_{cr} of the mixture must be determined. The critical pressure and critical temperature can be determined by equation 3.12 and 3.13:

$$\sum y_i \, P_{cr} \tag{3.12}$$

and

$$\sum y_i T_{cr} \tag{3.13}$$

These values will then be used in the Schultz Compressibility Factor – Function X versus Reduced Pressure graph and Schultz Compressibility Factor – Function Y versus Reduced Pressure graph which are automatically interpolated by the predicting tool.

3.3.2 Schultz Polytropic Head Analysis

When calculating polytopic head, Shultz analysis introduced the polytropic volume exponent as follows:

$$n_v = \frac{(1+X)}{Y\left[\frac{1}{k}\left(\frac{1}{\eta_p}+X\right)-\left(\frac{1}{\eta_p}-1\right)\right]} \tag{3.14}$$

On top of that, a correction factor, f is introduced to account for slight variation in n_v as follows:

$$f = \frac{(k_v-1)(h_{2s}-h_1)}{k_v(p_2v_{2s}-p_1v_1)} \; where \; k_v = \frac{k}{Y} \tag{3.15}$$

Next, the Schultz polytropic head calculation took into account the polytropic volume exponent and correction factor calculated before, as shown in the following equation:

$$H_p = fZRT_1\left[\frac{n_v}{n_v-1}\right]\left[\left(\frac{P_2}{P_1}\right)^{\frac{n_v-1}{n_v}} - 1\right] \tag{3.16}$$

3.4 Gas Power

The Gas Power consumed by the compressor is then calculated by equation 3.17.

$$Power_{gas} = \frac{H_{poly}.\dot{M}}{\eta_{poly}} \tag{3.17}$$

3.5 Required Input and Expected Output

Table 3.1 shows required input and expected output of the predicting tool.

Table 3.1 Required Input and Expected Output

Input	Output
Suction Pressure, Ps	Polytropic Head
Suction Temperature, Ts	Polytropic Efficiency
Discharge Pressure, Pd	Gas Power
Discharge Temperature, Td	Polytropic Head Deviation
Actual Mass Flow Rate, m	Polytropic Efficiency Deviation
Compressor Speed, N	Gas Power Deviation
Gas Composition	

3.6 Tools & Equipment

This project requires data or trending analysis as a solution for maintenance plan. Some tools or sources required as the following:

i. Microsoft Excel
ii. Microsoft Visual Basic Application
iii. Historical Data of Centrifugal Compressor
iv. Centrifugal Compressor Data Sheet and Design Performance

3.7 Key Milestones

Figure 3.2 shows the Project Key Milestones of the predicting tool development from January to August 2014.

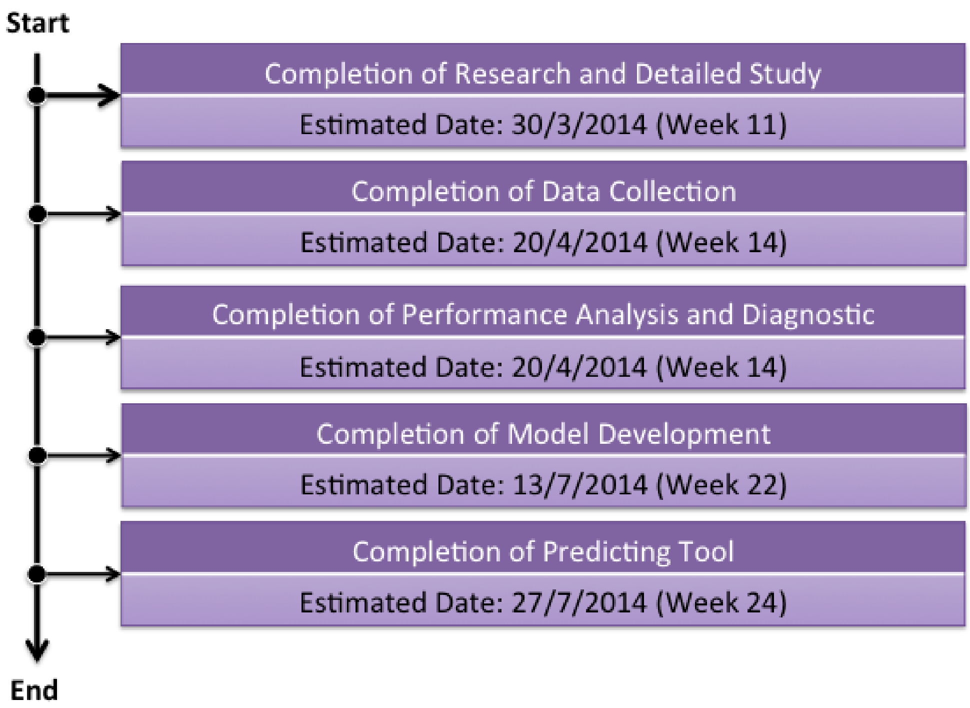

Figure 3.2 Project Key Milestones

3.8 Project Gantt Chart

Table 3.2 shows detailed Gantt Chart of the Predicting Tool development.

Table 3.2 Project Gantt Chart

FYP Gantt Chart

Activities	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28
Preliminary Research			■	■	■																							
Detailed Study						■	■	■	■	■	■																	
Symptoms and Causes						■	■																					
Effect in Performance								■	■																			
Mitigation and Solution										■	■																	
Data Collection								■	■	■	■	■	■	■														
Performance Analysis and Diagnostic										■	■	■	■	■														
Study of Performance Analysis Method										■	■																	
Data Analysis												■	■	■														
Performance Calculation													■	■														
Model Development															■	■	■	■	■	■	■	■						
Design Performance Curve															■													
Graphical User Interface Development																■	■	■	■	■	■	■						
Predicting Tool																					■	■	■	■				
Mapping of Operational and Design Performance																					■	■	■	■				

CHAPTER 4
RESULTS AND DISCUSSION

This chapter discusses results of this project, which includes calculation involved in developing the predicting tool to analyze the centrifugal compressor performance. For this purpose, an example of operating condition of a low pressure compressor at a particular time will be used for discussion as per below:

- Date and Time: 2/8/2014 00:00 AM
- Suction Pressure: 223.66 psia
- Suction Temperature: 548.30 $°R$
- Discharge Pressure: 701.36 psia
- Discharge Temperature: 711.68 $°R$
- Inlet Flow: 4010 ACFM

Detailed calculations of the Predicting Tool are further discussed in this chapter starting from Gas Composition handled by the compressor. Units used in the calculations are of imperial units to suit the performance curve provided by PETRONAS Carigali, Kerteh.

4.1 Gas Analysis

4.1.1 Molar Mass of Gas Mixture

For gas analysis calculation, the mole fraction of each gas type is required from the user. Based on these inputs, the molar mass of the individual gas is first calculated to get the molar mass of the gas mixture. The molar mass of the mixture is calculated by using equation 3.1 and calculation summary is shown in Table 4.1:

Table 4.1 Molar Mass Analysis of Gas Mixture

Gas Type	Molar mass, Mi [lbm/lbmol]	Mole fraction, yi (mol)	Mm = ∑ [lbm/lbmol]
Methane	16.043	0.803289	12.89
Ethane	30.02	0.078591	2.36
Propane	44.097	0.041826	1.84
i-Butane	58.124	0.012988	0.75
n-Butane	58.124	0.007581	0.44
i-Pentane	72.151	0.003218	0.23
n-Pentane	72.151	0.001498	0.11
Hexane	86.178	0.002671	0.23
Nitrogen	28.013	0.006344	0.18
Carbon Dioxide	44.01	0.041994	1.85
TOTAL		**1**	**20.88**

As shown in the Table 4.1 above, the molar mass of the gas mixture is 20.88 lbmol/lbm.

4.1.2 *Gas Constant of Gas Mixture*

Next, the gas constant of the mixture, is calculated using equation 3.2 as shown below:

$$R_m = \frac{1.98588 \frac{\text{Btu}}{\text{lbmol}} \cdot \text{R}}{20.88 \frac{lbmol}{lbm}} = 0.095 \frac{Btu}{lbm} . R$$

4.1.3 *Specific Heats Capacity*

The mass fraction of individual gas is calculated by dividing individual molar mass of gas with molar mass of the mixture using equation 3.3. Then, specific heat capacity at constant pressure of individual gas, $c_{p,i}$ is calculated, by equation 3.4. Each value of the $c_{p,i}$ is then multiplied with mass fraction of each gas type. The total of these individual specific heats will produce specific heat capacity at constant pressure of the mixture, $c_{p,m}$. Table 4.2 shows summary of calculation for specific heat capacity of the gas mixtures.

Table 4.2 Ideal Gas Specific Heats of Gas Mixture

Gas Type	Mass Fraction, mf	Ideal-Gas Specific Heats as a Function of Temperature						
		a	b	c	d	Temperature (R)	Cp,i [Btu/lbm. R]	Cp,m = ∑mfi Cpi [Btu/lbm. R]
Methane	0.62	4.75	0.006666	9.352E-07	-4.51E-10	629.991126	0.57	0.35
Ethane	0.11	1.648	0.02291	-0.000004722	2.984E-10	629.991126	0.48	0.05
Propane	0.09	-0.966	0.04044	-0.00001159	1.3E-09	629.991126	0.46	0.04
i-Butane	0.04	-1.89	0.0552	-0.00001696	2.044E-09	629.991126	0.46	0.02
n-Butane	0.02	0.945	0.04929	-0.00001352	1.433E-09	629.991126	0.46	0.01
i-Pentane	0.01	1.618	0.06028	-0.00001656	1.732E-09	629.991126	0.46	0.01
n-Pentane	0.01	1.618	0.06028	-0.00001656	1.732E-09	629.991126	0.46	0.00
Hexane	0.01	1.657	0.07328	-0.00002112	2.363E-09	629.991126	0.46	0.01
Nitrogen	0.01	6.903	-0.0002085	5.957E-07	-1.176E-10	629.991126	0.25	0.00
Carbon Dioxide	0.09	5.316	0.0079361	-0.000002581	3.059E-10	629.991126	0.21	0.02
TOTAL	**1.00**							**0.51**

Based on the above calculation, the specific heat at constant pressure, $c_{p,m}$ of the gas mixture is found to be 0.51 Btu/lbm.R. This value is then used to calculate the specific heat at constant volume, $c_{v,m}$ of the mixture by using equation 3.5:

$$c_{v,m} = 0.51\frac{Btu}{lbm}.R - 0.095\frac{Btu}{lbm}.R = 0.413\frac{Btu}{lbm}.R$$

Finally, the ratio of $c_{p,m}$ and $c_{v,m}$ is calculated using equation 3.6:

$$k = \frac{c_p}{c_v} = \frac{0.51\frac{Btu}{lbm}.R}{0.413\frac{Btu}{lbm}.R} = 1.23 \tag{4.6}$$

4.2 Polytropic Efficiency

The polytropic efficiency of the compressor is calculated using equation 3.7 as shown below:

$$\eta_{poly} = \frac{1.23-1}{1.23}\frac{ln\left(\frac{701.36\ psia}{223.66\ psia}\right)}{ln\left(\frac{711.68\ R}{548.30\ R}\right)} = 0.82$$

4.3 Schultz Polytropic Analysis

4.3.1 Schultz Compressibility Factor

The critical pressure, P_{cr} and critical temperature, T_{cr} of the mixture are determined by equation 3.12 and 3.13 as summarized in Table 4.3:

Table 4.3 Critical Pressure and Critical Temperature for Gas Mixture

Critical Pressure, Pcr,i [psia]	Critical Pressure, Pcr,m = ∑ yi Pcr,i [psia]	Critical Temperature, Tcr,i [R]	Critical Temperature, Tcr,m = ∑ yi Tcr,i [R]
673.00	540.61	343.90	276.25
708.00	55.64	549.80	43.21
617.00	25.81	665.90	27.85
529.10	6.87	734.70	9.54
551.00	4.18	765.20	5.80
490.40	1.58	828.80	2.67
464.00	0.70	781.11	1.17
439.00	1.17	914.20	2.44
492.00	3.12	227.10	1.44
1,071.00	44.98	547.50	22.99
	684.65		**393.37**

The critical pressure, P_{cr} for this gas composition is 684.65 psia while the critical temperature, T_{cr} is 393.37 $°R$. From these values, reduced pressure P_r and reduced temperature, T_r are calculated using equation 3.10 and 3.11 as follows:

$$Reduced\ Pressure, P_r = \frac{223.66}{684.65} = 0.33\ psia$$

$$Reduced\ Temperature, T_r = \frac{548.3}{393.37} = 1.39\ °R$$

The predicting tool will interpolate these values automatically to return value of X factor and Y factor from the Schultz Compressibility Factor – Function X versus Reduced Pressure graph and Schultz Compressibility Factor – Function Y versus Reduced Pressure graph. Therefore, based on the interpolations:

- X factor is 0.1 and
- Y factor is 1.035.

4.3.2 Schultz Polytropic Analysis

Using equation 3.14, the polytropic exponent n_v is calculated as follows:

$$n_v = \frac{(1+0.1)}{1.035\left[\frac{1}{1.23}\left(\frac{1}{0.82}+0.1\right)-\left(\frac{1}{0.82}-1\right)\right]} = 1.24$$

As for the correction factor, f, it is calculated by using equation 3.15:

$$f = \frac{(1.19-1)(345.25-278.81)}{1.19((701.36)(0.09)-(223.66)(0.23))} \; where \; k_v = \frac{1.23}{1.035}$$

$$f = 0.85 \; where \; k_v = 1.19$$

Next, the Polytropic head is calculated by equation 3.16 as per below:

$$H_p = (1.19)(1.0)(0.095)(548.30)\left[\frac{1.24}{1.24-1}\right]\left[\left(\frac{701.36}{223.66}\right)^{\frac{1.24-1}{1.24}}-1\right]$$

$$H_p = 43\,910.76 \; ft.lbs/lb$$

Hence, the polytopic head for this operating condition is found to be 43 910.76 ft.lbs/lb.

4.4 Gas Power

Finally, the Gas Power consumed by the compressor is calculated by equation 3.17:

$$Power_{gas} = \frac{(43\,910.76\; ft.lbs/lb)(4010\; ACFM)}{0.82} = 5167.24\; hp$$

4.5 Design of Performance Curve

In order to analyze the performance deviation, designed performance curve is required for comparison purpose. The operating conditions of performance of the compressor will then be plotted on the design performance curve. As the performance curve is only provided by the manufacturer, the author is required to model the performance curve in Microsoft excel. PETRONAS Angsi has two compressors, which are Low Pressure Compressor and High Pressure Compressor.

4.5.1 Low Pressure Compressor

The following figure shows Low Pressure Compressor of PETRONAS Angsi:

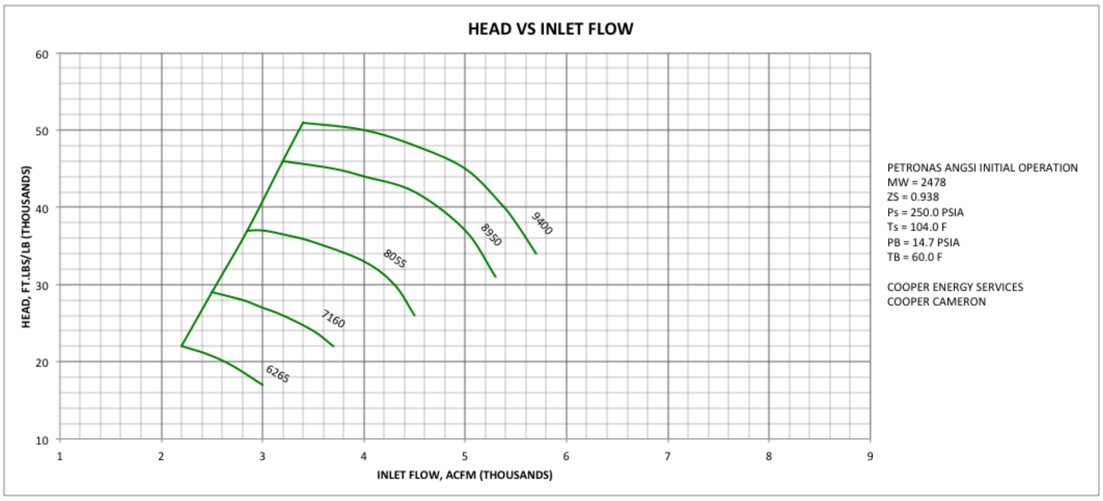

Figure 4.1 Designed Performance Curve of LP Compressor

4.5.2 High Pressure Compressor

The following figure shows High Pressure Compressor of PETRONAS Angsi:

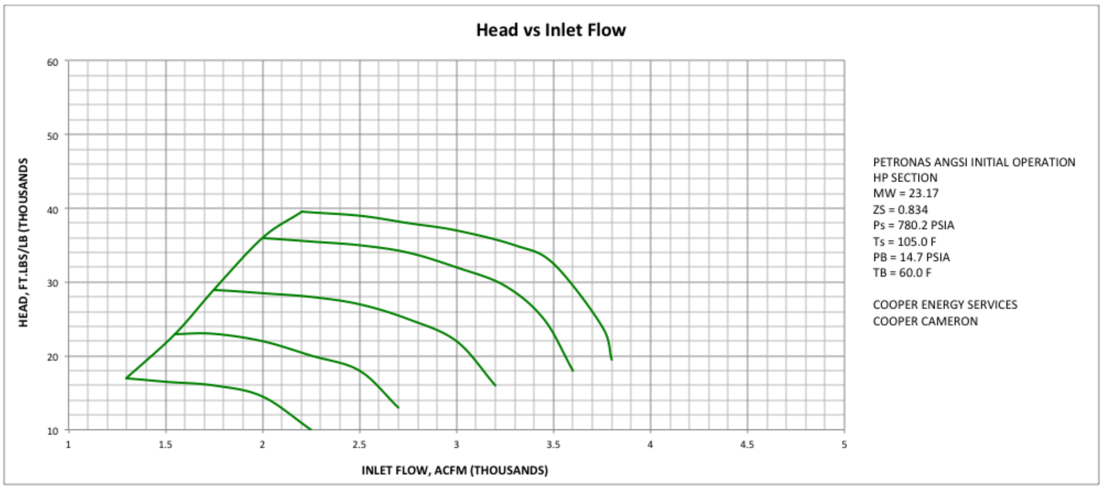

Figure 4.2 Designed Performance Curve of HP Compressor

These performance maps will be used to map actuql operating conditions of the compressor at different times. From these graphs, deviation of compressor performance can be evaluated.

4.6 Predicting Tool

Using Microsoft Excel and Visual Basic Application, a Graphical User Interface is created as shown in Figure 4.3.

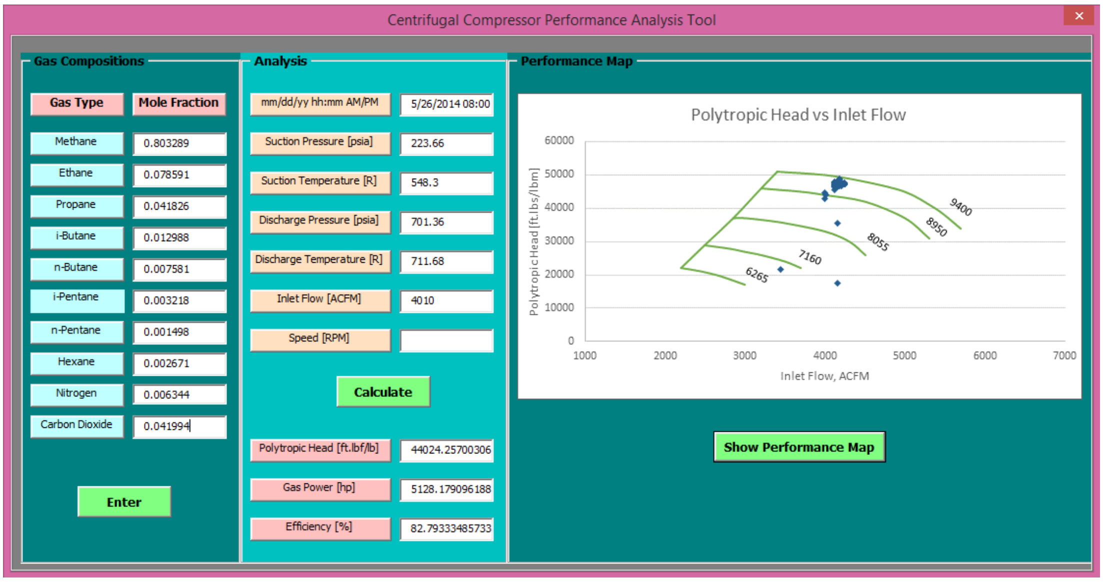

Figure 4.3 Centrifugal Compressor Performance Analysis Tool

The predicting tool starts by user opening the excel file and by clicking "username" command button, a userform as shown in Figure 4.3 will be displayed, while the excel file will hide. Next, user needs to enter gas composition and when the enter button is clicked, the gas composition is stored in excel database. Then, the predicting tool requires user to enter compressor input with Date and Time, Suction Pressure, Suction Temperature, Discharge Pressure, Discharge Temperature, Inlet Flow and Speed of the compressor. When user clicks the calculate button, the predicting tool will store data in excel file and calculate the compressor performance. The values of Schultz Compressibility Factor X and Y are interpolated by the predicting tool, therefore, users do not need to manually input these values. Based on the calculation, the Polytropic Analysis will be displayed in the userform. Clicking the "Show Performance Map" will display the Polytropic analysis result in performance map. If user wants to enter new data, he needs to repeat the compressor input process. Otherwise, he needs to save the file and exit the program.

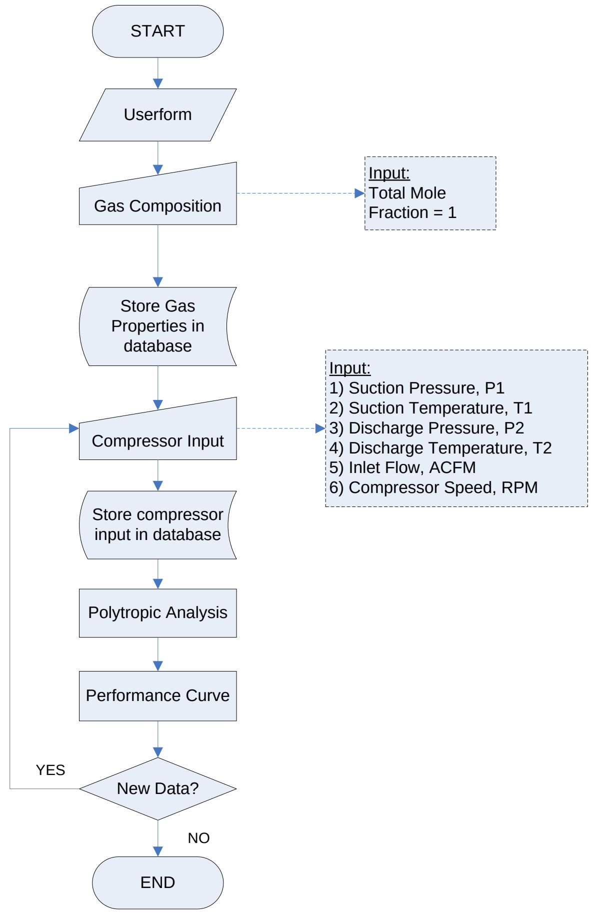

Figure 4.4 Predicting Tool Algorithm

4.7 Performance Analysis

4.7.1 Low Pressure Compressor

Figure 4.5 shows result from the predicting tool performance analysis tabulated into the performance curve of low pressure compressor of PETRONAS Angsi from 8th February 2014 to 25th May 2014.

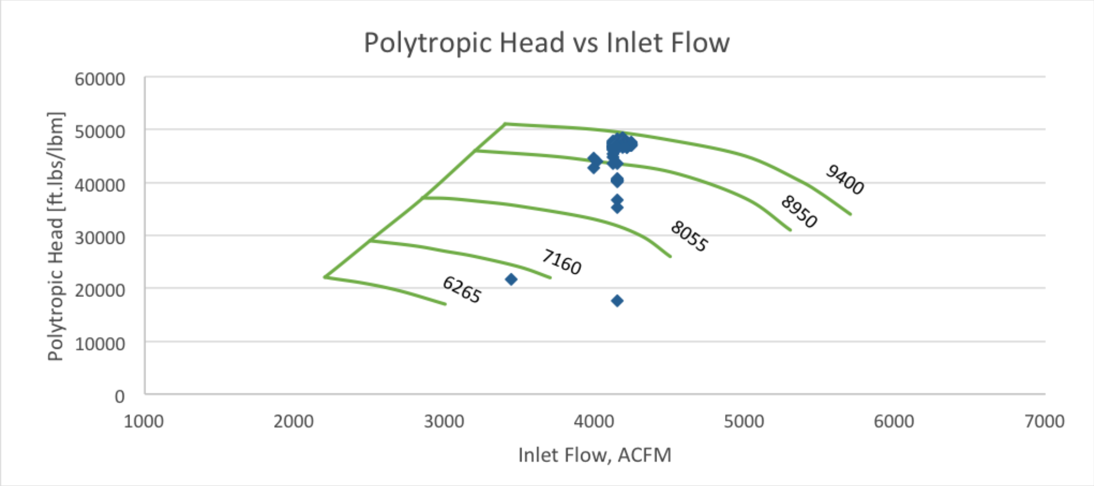

Figure 4.5 Polytropic Head Analysis of Low Pressure Compressor

Based on the graph in Figure 4.5 above, the compressor is operating at mostly designed speed and polytopic head. Only at certain condition the compressor experienced low polytropic head at high and low inlet flow rate. On top of that, the polytropic efficiency of the compressor is in the range of 80% for almost all conditions. Therefore, it can be said that the compressor is operating at optimum condition. The summary analysis of low pressure compressor can be referred in Appendix H which consists of Polytropic Head, Gas Power and Efficiency.

4.7.2 High Pressure Compressor

Figure 4.6 shows result from the predicting tool performance analysis tabulated into the performance curve of low pressure compressor of PETRONAS Angsi from 8th February 2014 to 25th May 2014.

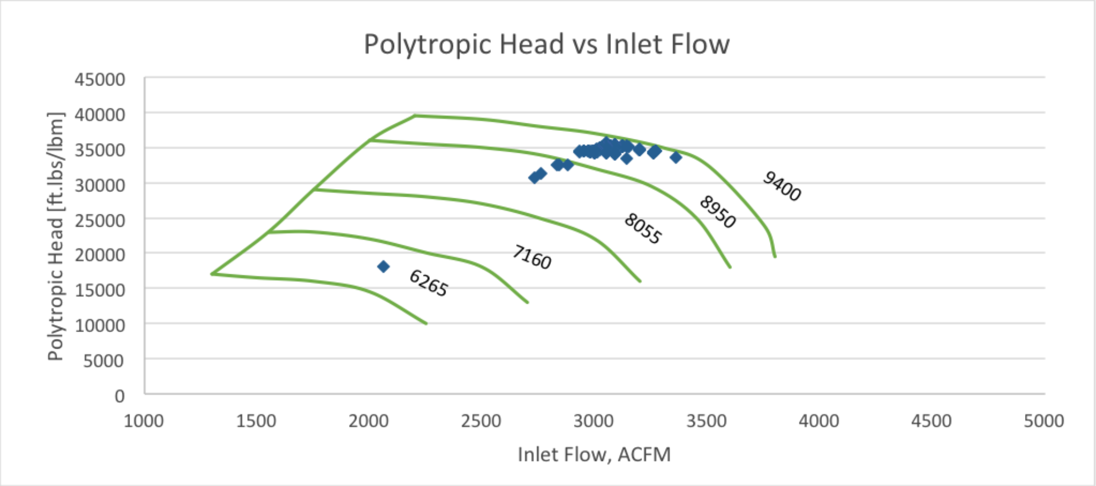

Figure 4.6 Polytropic Head Analysis of High Pressure Compressor

Based on the graph in Figure 4.6, the compressor is operating at mostly designed speed and polytopic head. However, at certain condition, the actual polytropic head is lower than designed condition. On top of that, the polytropic efficiency of the compressor is in the range of 70% to 75% for almost all conditions. The high pressure compressor efficiency is not as high as low pressure compressor, but still operating at acceptable efficiency. The summary analysis of high pressure compressor is included in Appendix I which consists of Polytropic Head, Gas Power and Efficiency.

CHAPTER 5
CONCLUSION AND RECOMMENDATION

Monitoring performance is one of the methods to maintain health of a centrifugal compressor. In this project, the centrifugal compressor is modeled by using thermodynamics principle to analyze the performance. On top of that, the performance analysis used Schultz Polytropic Analysis approach which is in reference to the ASME PTC 10 for centrifugal compressor. The predicting tool was developed by using Microsoft Excel with the Graphical User Interface coded in Visual Basic Application. The predicting tool developed is able to analyze Polytropic Head, Polytropic Efficiency and Gas Power of the centrifugal compressor.

Based on the analysis done, both low pressure and high pressure compressors are operating at optimum condition. However, there are certain conditions where the head are lower than they should be and the efficiency of HP compressor is quite low at 70% to 75% compared to LP compressor which is in the range of 80% to 85%. Therefore, the operator is recommended to monitor and investigate the reasons of these occurrences as the predicting tool is able to analyze performance of the centrifugal compressor.

However, due to insufficient data by collaborating company, it is hard to conclude that the performance of the compressor is deteriorating when the polytropic head is lower. This is because the polytropic head might be low due to lower speed and inlet volume. Therefore, the predicting tool should include analysis of polytropic head at specific speed as shown in Figure 5.1.

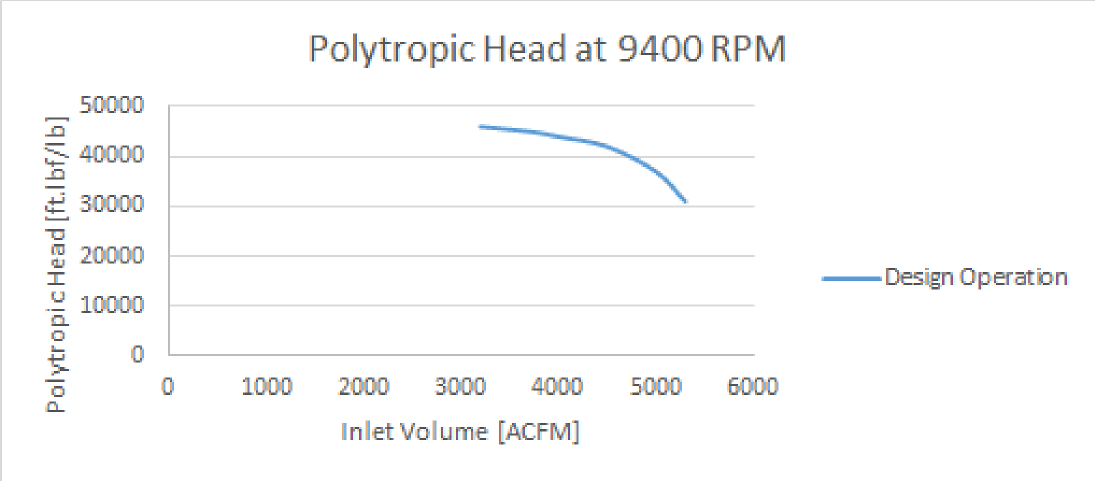

Figure 5.1 Recommendation of Polytropic Head Analysis

Based on Figure 5.1, the blue line indicates designed Polytropic Head at speed of 9400 RPM. The operating polytropic head of actual operation can be indicated by different line in the same graph where deviation of compressor performance is indicated by shifted line below designed operation.

On top of that, the study of compressor performance can be narrowed down to effect of fouling in compressor performance. This is because fouling is one of contributing factors in performance deterioration. Fouling in compressor can be detected by increased discharge temperature as compared to designed discharge temperature. With sufficient data, hopefully the predicting tool will be able to analyze the compressor performance and detect fouling in compressor.

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APPENDICES

APPENDIX A

SCHULTZ COMPRESSIBILITY FACTOR – FUNCTION Y

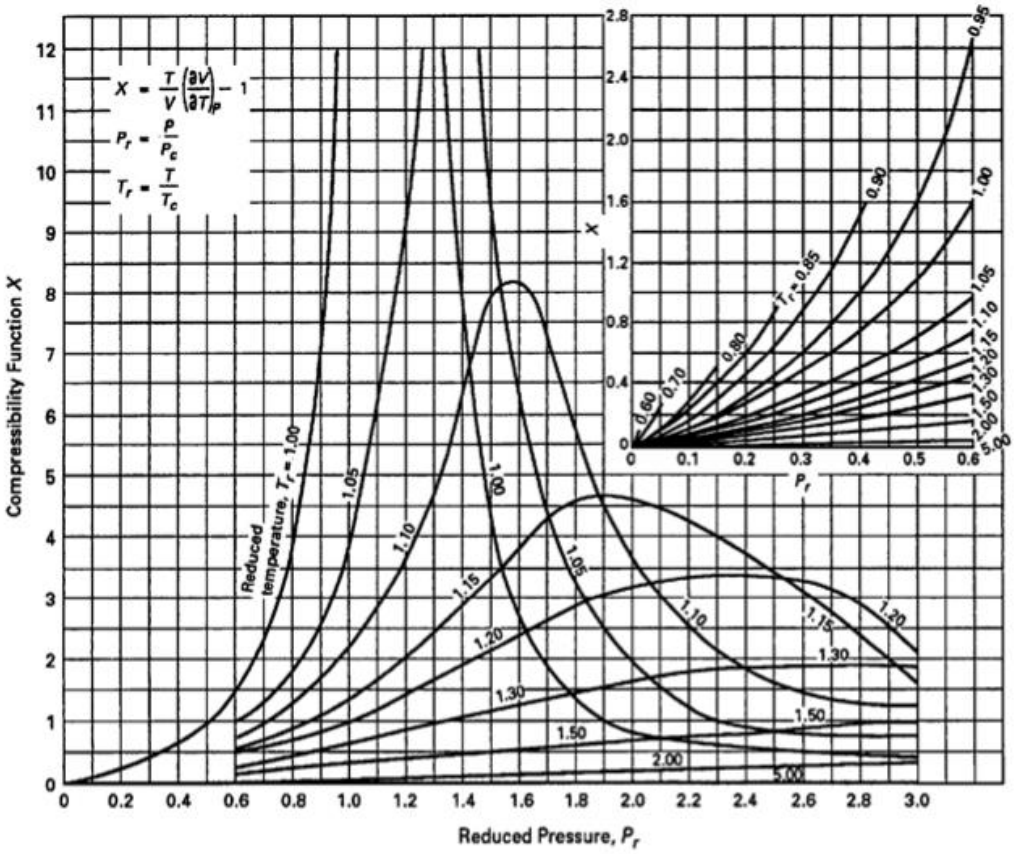


FIG. 3.6 SCHULTZ COMPRESSIBILITY FACTOR — FUNCTION *Y* VERSUS REDUCED PRESSURE

APPENDIX B

SCHULTZ COMPRESSIBILITY FACTOR – FUNCTION X

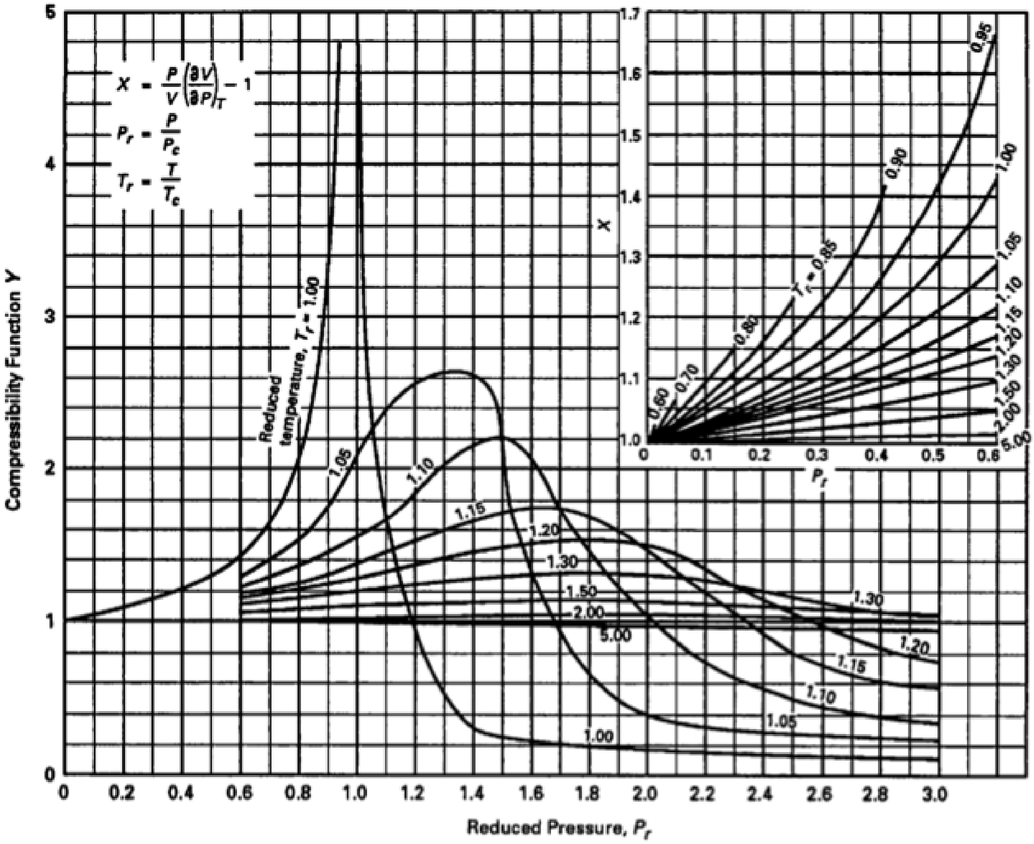
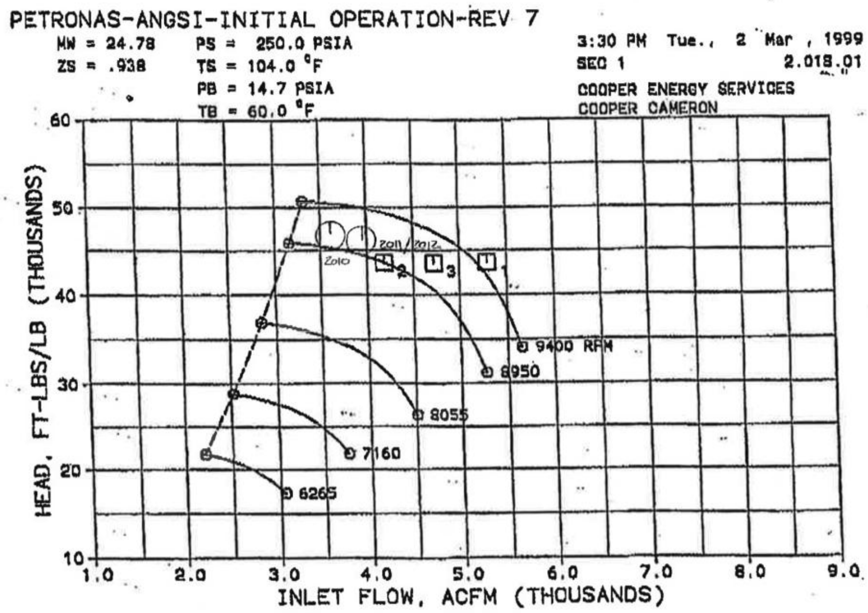


FIG. 3.7 SCHULTZ COMPRESSIBILITY FACTOR — FUNCTION *X* VERSUS REDUCED PRESSURE

APPENDIX C

PETRONAS ANGSI PERFORMANCE CURVE (LOW PRESSURE)

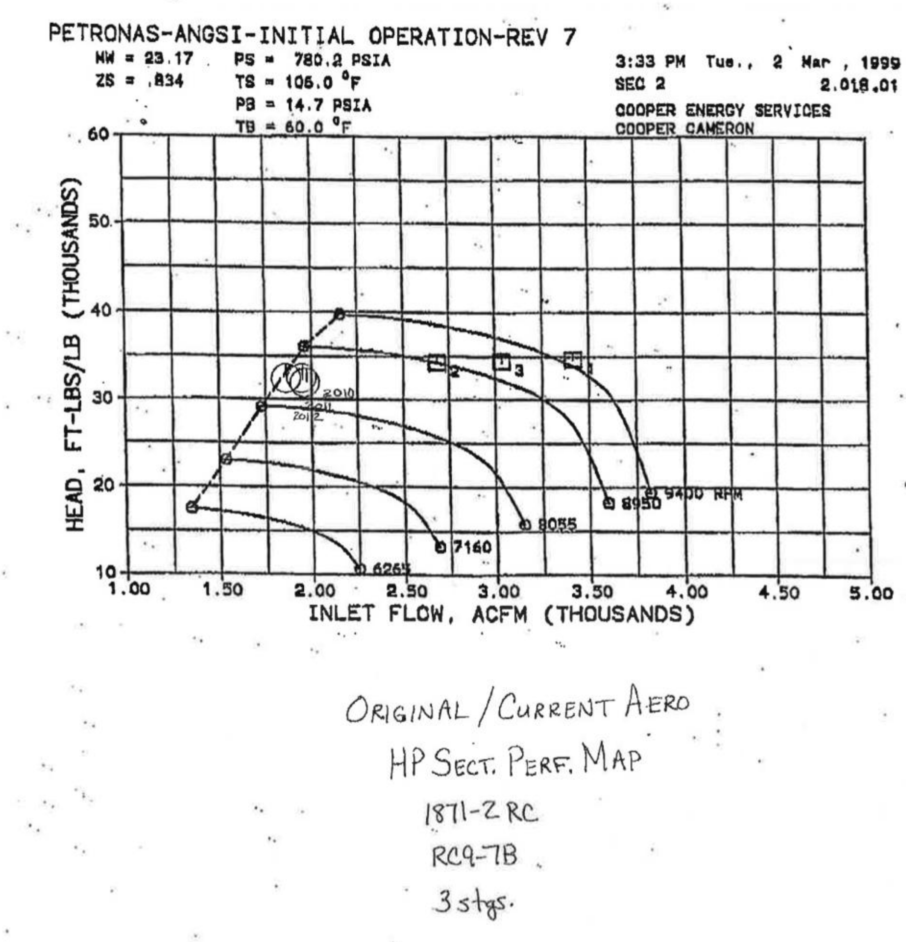


ORIGINAL / CURRENT AERO
LP SECT. PERF. MAP
1871-2 RC
RC9-7B
4stgs.

Gear ratio = 1.811
Speed ⇒ PT = 5183.2 rpm
comp speed = 9386.7 rpm

APPENDIX D

PETRONAS ANGSI PERFORMANCE CURVE (HIGH PRESSURE)



APPENDIX E

MOLAR MASS, GAS CONSTANT AND CRITICAL POINT PROPERTIES

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TABLE A–1E

Molar mass, gas constant, and critical-point properties

Substance	Formula	Molar mass, *M* lbm/lbmol	*Gas constant, R* Btu/lbm · R*	psia · ft^3/lbm · R*	*Critical-point properties* Temperature, R	Pressure, psia	Volume, ft^3/lbmol
Air	—	28.97	0.06855	0.3704	238.5	547	1.41
Ammonia	NH_3	17.03	0.1166	0.6301	729.8	1636	1.16
Argon	Ar	39.948	0.04971	0.2686	272	705	1.20
Benzene	C_6H_6	78.115	0.02542	0.1374	1012	714	4.17
Bromine	Br_2	159.808	0.01243	0.06714	1052	1500	2.17
n-Butane	C_4H_{10}	58.124	0.03417	0.1846	765.2	551	4.08
Carbon dioxide	CO_2	44.01	0.04513	0.2438	547.5	1071	1.51
Carbon monoxide	CO	28.011	0.07090	0.3831	240	507	1.49
Carbon tetrachloride	CCl_4	153.82	0.01291	0.06976	1001.5	661	4.42
Chlorine	Cl_2	70.906	0.02801	0.1517	751	1120	1.99
Chloroform	$CHCl_3$	119.38	0.01664	0.08988	965.8	794	3.85
Dichlorodifluoromethane (R-12)	CCl_2F_2	120.91	0.01643	0.08874	692.4	582	3.49
Dichlorofluoromethane (R-21)	$CHCl_2F$	102.92	0.01930	0.1043	813.0	749	3.16
Ethane	C_2H_6	30.020	0.06616	0.3574	549.8	708	2.37
Ethyl alcohol	C_2H_5OH	46.07	0.04311	0.2329	929.0	926	2.68
Ethylene	C_2H_4	28.054	0.07079	0.3825	508.3	742	1.99
Helium	He	4.003	0.4961	2.6809	9.5	33.2	0.926
n-Hexane	C_6H_{14}	86.178	0.02305	0.1245	914.2	439	5.89
Hydrogen (normal)	H_2	2.016	0.9851	5.3224	59.9	188.1	1.04
Krypton	Kr	83.80	0.02370	0.1280	376.9	798	1.48
Methane	CH_4	16.043	0.1238	0.6688	343.9	673	1.59
Methyl alcohol	CH_3OH	32.042	0.06198	0.3349	923.7	1154	1.89
Methyl chloride	CH_3Cl	50.488	0.03934	0.2125	749.3	968	2.29
Neon	Ne	20.183	0.09840	0.5316	80.1	395	0.668
Nitrogen	N_2	28.013	0.07090	0.3830	227.1	492	1.44
Nitrous oxide	N_2O	44.013	0.04512	0.2438	557.4	1054	1.54
Oxygen	O_2	31.999	0.06206	0.3353	278.6	736	1.25
Propane	C_3H_8	44.097	0.04504	0.2433	665.9	617	3.20
Propylene	C_3H_6	42.081	0.04719	0.2550	656.9	670	2.90
Sulfur dioxide	SO_2	64.063	0.03100	1.1675	775.2	1143	1.95
Tetrafluoroethane (R-134a)	CF_3CH_2F	102.03	0.01946	0.1052	673.6	588.7	3.19
Trichlorofluoromethane (R-11)	CCl_3F	137.37	0.01446	0.07811	848.1	635	3.97
Water	H_2O	18.015	0.1102	0.5956	1164.8	3200	0.90
Xenon	Xe	131.30	0.01513	0.08172	521.55	852	1.90

*Calculated from $R = R_u/M$, where R_u = 1.98588 Btu/lbmol · R = 10.7316 psia · ft^3/lbmol · R and *M* is the molar mass.

Source: K. A. Kobe and R. E. Lynn, Jr., *Chemical Review* 52 (1953), pp. 117–236, and ASHRAE, *Handbook of Fundamentals* (Atlanta, GA: American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc., 1993), pp. 16.4 and 36.1.

APPENDIX F

IDEAL GAS SPECIFIC HEATS OF VARIOUS COMMON GASSES AS A FUNCTION OF TEMPERATURE

TABLE A–2E

Ideal-gas specific heats of various common gases (*Concluded*)
(*c*) As a function of temperature

$$\bar{c}_p = a + bT + cT^2 + dT^3$$

(T in R, c_p in Btu/lbmol · R)

Substance	Formula	a	b	c	d	Temperature range, R	% error Max.	% error Avg.
Nitrogen	N_2	6.903	-0.02085×10^{-2}	0.05957×10^{-5}	-0.1176×10^{-9}	491-3240	0.59	0.34
Oxygen	O_2	6.085	0.2017×10^{-2}	-0.05275×10^{-5}	0.05372×10^{-9}	491-3240	1.19	0.28
Air	—	6.713	0.02609×10^{-2}	0.03540×10^{-5}	-0.08052×10^{-9}	491-3240	0.72	0.33
Hydrogen	H_2	6.952	-0.02542×10^{-2}	0.02952×10^{-5}	-0.03565×10^{-9}	491-3240	1.02	0.26
Carbon monoxide	CO	6.726	0.02222×10^{-2}	0.03960×10^{-5}	-0.09100×10^{-9}	491-3240	0.89	0.37
Carbon dioxide	CO_2	5.316	0.79361×10^{-2}	-0.2581×10^{-5}	0.3059×10^{-9}	491-3240	0.67	0.22
Water vapor	H_2O	7.700	0.02552×10^{-2}	0.07781×10^{-5}	-0.1472×10^{-9}	491-3240	0.53	0.24
Nitric oxide	NO	7.008	-0.01247×10^{-2}	0.07185×10^{-5}	-0.1715×10^{-9}	491-2700	0.97	0.36
Nitrous oxide	N_2O	5.758	0.7780×10^{-2}	-0.2596×10^{-5}	0.4331×10^{-9}	491-2700	0.59	0.26
Nitrogen dioxide	NO_2	5.48	0.7583×10^{-2}	-0.260×10^{-5}	0.322×10^{-9}	491-2700	0.46	0.18
Ammonia	NH_3	6.5846	0.34028×10^{-2}	0.073034×10^{-5}	-0.27402×10^{-9}	491-2700	0.91	0.36
Sulfur	S_2	6.499	0.2943×10^{-2}	-0.1200×10^{-5}	0.1632×10^{-9}	491-3240	0.99	0.38
Sulfur dioxide	SO_2	6.157	0.7689×10^{-2}	-0.2810×10^{-5}	0.3527×10^{-9}	491-3240	0.45	0.24
Sulfur trioxide	SO_3	3.918	1.935×10^{-2}	-0.8256×10^{-5}	1.328×10^{-9}	491-2340	0.29	0.13
Acetylene	C_2H_2	5.21	1.2227×10^{-2}	-0.4812×10^{-5}	0.7457×10^{-9}	491-2700	1.46	0.59
Benzene	C_6H_6	−8.650	6.4322×10^{-2}	-2.327×10^{-5}	3.179×10^{-9}	491-2700	0.34	0.20
Methanol	CH_4O	4.55	1.214×10^{-2}	-0.0898×10^{-5}	-0.329×10^{-9}	491-1800	0.18	0.08
Ethanol	C_2H_6O	4.75	2.781×10^{-2}	-0.7651×10^{-5}	0.821×10^{-9}	491-2700	0.40	0.22
Hydrogen chloride	HCl	7.244	-0.1011×10^{-2}	0.09783×10^{-5}	-0.1776×10^{-9}	491-2740	0.22	0.08
Methane	CH_4	4.750	0.6666×10^{-2}	0.09352×10^{-5}	-0.4510×10^{-9}	491-2740	1.33	0.57
Ethane	C_2H_6	1.648	2.291×10^{-2}	-0.4722×10^{-5}	0.2984×10^{-9}	491-2740	0.83	0.28
Propane	C_3H_8	−0.966	4.044×10^{-2}	-1.159×10^{-5}	1.300×10^{-9}	491-2740	0.40	0.12
n-Butane	C_4H_{10}	0.945	4.929×10^{-2}	-1.352×10^{-5}	1.433×10^{-9}	491-2740	0.54	0.24
i-Butane	C_4H_{10}	−1.890	5.520×10^{-2}	-1.696×10^{-5}	2.044×10^{-9}	491-2740	0.25	0.13
n-Pentane	C_5H_{12}	1.618	6.028×10^{-2}	-1.656×10^{-5}	1.732×10^{-9}	491-2740	0.56	0.21
n-Hexane	C_6H_{14}	1.657	7.328×10^{-2}	-2.112×10^{-5}	2.363×10^{-9}	491-2740	0.72	0.20
Ethylene	C_2H_4	0.944	2.075×10^{-2}	-0.6151×10^{-5}	0.7326×10^{-9}	491-2740	0.54	0.13
Propylene	C_3H_6	0.753	3.162×10^{-2}	-0.8981×10^{-5}	1.008×10^{-9}	491-2740	0.73	0.17

Source: Chemical and Process Thermodynamics 3/E by Kyle, B. G., © 2000. Adapted by permission of Pearson Education, Inc., Upper Saddle River, NJ.

APPENDIX G

GRAPHICAL USER INTERFACE PROGRAM

```
Private Sub ComboBox1_Change()
End Sub
Private Sub ListBox1_Click()
End Sub
Private Sub TxtGasType_Change()
End Sub
Private Sub TabStrip1_Change()
End Sub
Private Sub ComboBox5_Change()
End Sub
Private Sub ComboBox8_Change()
End Sub
Private Sub cmdGraph_Click()
Set CurrentChart = Sheets("Performance Map").ChartObjects(1).Chart
    Fname = ThisWorkbook.Path & "\temp.gif"
    CurrentChart.Export Filename:=Fname, FilterName:="GIF"
    Image1.Picture = LoadPicture(Fname)
End Sub
Private Sub cmdWorkbook_Click()
Application.Visible = True
Me.Hide
End Sub
Private Sub CommandButton1_Click()
Sheet1.Range("d5") = TextBox1.Value
Sheet1.Range("d6") = TextBox2.Value
Sheet1.Range("d7") = TextBox3.Value
Sheet1.Range("d8") = TextBox4.Value
Sheet1.Range("d9") = TextBox5.Value
Sheet1.Range("d10") = TextBox6.Value
Sheet1.Range("d11") = TextBox7.Value
Sheet1.Range("d12") = TextBox8.Value
Sheet1.Range("d13") = TextBox9.Value
Sheet1.Range("d14") = TextBox10.Value
End Sub
Private Sub CommandButton2_Click()
Range("A1048576").End(xlUp).Offset(1, 0).Select
ActiveCell.Value = txtDate.Text
ActiveCell.Offset(0, 1).Value = txtPressure1.Text
ActiveCell.Offset(0, 2).Value = txtTemperature1.Text
ActiveCell.Offset(0, 3).Value = txtPressure2.Text
ActiveCell.Offset(0, 4).Value = txtTemperature2.Text
ActiveCell.Offset(0, 5).Value = txtInletFlow.Text
ActiveCell.Offset(0, 6).Value = txtSpeed.Text
txtHead.Text = ActiveCell.Offset(0, 23).Value
txtPower.Text = ActiveCell.Offset(0, 24).Value
txtEfficiency.Text = ActiveCell.Offset(0, 25).Value
Range("A2").Select
txtDate.Text = ""
txtPressure1.Text = ""
txtTemperature1.Text = ""
txtPressure2.Text = ""
txtTemperature2.Text = ""
txtInletFlow.Text = ""
txtSpeed.Text = ""
End Sub
Private Sub CommandButton3_Click()
UserForm1.TextBox17.Value = Sheet3.Range("af4")
UserForm1.TextBox18.Value = Sheet3.Range("ag4")
UserForm1.TextBox19.Value = Sheet3.Range("ah4")
End Sub
Private Sub Frame1_Click()
End Sub
Private Sub Image1_Click()
End Sub
Private Sub Label1_Click()
End Sub
Private Sub Label11_Click()
End Sub
```

```
Private Sub Label3_Click()
End Sub
Private Sub Label5_Click()
End Sub
Private Sub Label7_Click()
End Sub
Private Sub lblGasPower_Click()
End Sub
Private Sub lblMoleFraction_Click()
End Sub
Private Sub lblTemperature_Click()
End Sub
Private Sub lblTemperature1_Click()
End Sub
Private Sub TextBox1_Change()
End Sub
Private Sub TextBox11_Change()
End Sub
Private Sub TextBox15_Change()
End Sub
Private Sub TextBox16_Change()
End Sub
Private Sub TextBox3_Change()
End Sub
Private Sub TextBox4_Change()
End Sub
Private Sub TextBox7_Change()
End Sub
Private Sub UserForm_Click()
End Sub
```

APPENDIX H
LOW PRESSURE COMPRESSOR PERFORMANCE ANALYSIS

Time	Suction Pressure, Ps [psia]	Suction Temp, Ts [R]	Discharge Pressure, Pd [Pd]	Discharge Temp, Td[R]	Inlet Flow [ACFM]	Polytropic Head [ft.lbf/lbm]	Gas Power [hp]	Efficiency [%]
2/8/14 0:00	223.66	548.30	701.36	711.68	4010	43,911	5,167	82
2/8/14 16:00	208.20	559.93	683.86	729.96	4210	46,758	5,146	84
2/9/14 0:00	208.38	561.12	683.86	731.17	4210	46,816	5,140	84
2/9/14 8:00	209.03	561.42	684.86	731.20	4210	46,765	5,145	84
2/9/14 16:00	312.29	560.81	584.33	662.72	3440	21,663	3,486	84
2/10/14 0:00	205.58	551.86	686.68	725.39	4210	46,896	5,256	70
2/10/14 8:00	205.27	551.95	687.51	725.54	4210	47,011	5,250	82
2/10/14 16:00	205.43	555.48	687.36	728.39	4210	47,225	5,201	83
2/11/14 0:00	205.46	555.21	687.95	728.14	4210	47,233	5,205	83
2/11/14 8:00	205.99	555.38	688.74	728.17	4210	47,187	5,213	83
2/11/14 16:00	206.40	555.72	689.82	728.68	4210	47,200	5,225	83
2/12/14 0:00	206.96	556.10	689.82	728.73	4210	47,114	5,226	83
2/12/14 8:00	207.04	556.23	689.39	728.93	4210	47,085	5,229	83
2/12/14 16:00	228.48	554.55	719.45	721.29	3990	44,611	5,299	83
2/13/14 0:00	209.22	555.30	690.27	726.99	4180	46,625	5,225	82
2/13/14 8:00	206.53	554.63	689.52	727.88	4210	47,082	5,247	83
2/13/14 16:00	207.58	555.10	689.80	728.01	4180	46,926	5,222	83
2/14/14 0:00	207.49	556.62	690.03	729.23	4180	47,065	5,196	83
2/14/14 8:00	208.40	556.90	690.54	729.28	4180	46,936	5,210	83
2/14/14 16:00	207.99	556.23	689.99	728.75	4180	46,935	5,210	83
2/15/14 0:00	207.84	556.26	689.92	728.91	4180	46,965	5,210	83
2/15/14 8:00	208.04	556.48	690.80	728.97	4180	46,990	5,209	83
2/15/14 16:00	208.19	556.41	691.06	728.87	4180	46,969	5,212	83
2/16/14 0:00	208.44	556.74	691.84	729.24	4180	46,994	5,216	83
2/16/14 8:00	208.59	558.10	691.97	730.38	4180	47,070	5,201	83
2/16/14 16:00	209.07	557.93	693.09	730.21	4180	47,032	5,215	83
2/17/14 0:00	207.47	557.16	692.01	730.15	4210	47,232	5,240	83
2/17/14 8:00	205.89	555.56	691.77	728.96	4210	47,408	5,227	83
2/17/14 16:00	210.25	557.01	693.97	729.07	4180	46,783	5,245	83
2/18/14 0:00	211.14	557.79	695.19	729.72	4150	46,741	5,219	83
2/18/14 8:00	209.64	556.63	694.23	729.06	4180	46,894	5,245	83
2/18/14 16:00	210.12	557.33	694.42	729.75	4180	46,867	5,250	83
2/19/14 0:00	210.19	557.32	694.52	729.49	4180	46,851	5,245	83
2/19/14 8:00	210.01	557.47	694.51	729.86	4180	46,903	5,245	83
2/19/14 16:00	210.01	556.94	694.40	729.28	4180	46,854	5,249	83
2/20/14 0:00	209.48	556.25	693.76	728.84	4180	46,871	5,249	83
2/20/14 8:00	208.79	555.03	693.12	727.88	4180	46,879	5,251	83
2/20/14 16:00	209.35	555.64	693.30	728.24	4180	46,825	5,251	83
2/21/14 0:00	209.63	556.47	693.74	729.10	4180	46,860	5,252	83
2/21/14 8:00	209.60	556.41	693.90	729.07	4180	46,872	5,253	83
2/21/14 16:00	209.61	556.62	694.31	729.21	4180	46,906	5,249	83

2/22/14 0:00	209.92	556.82	694.53	729.27	4180	46,873	5,251	83
2/22/14 8:00	209.06	556.31	694.33	728.88	4180	46,988	5,238	83
2/22/14 16:00	209.84	557.62	694.42	729.96	4180	46,940	5,238	83
2/23/14 0:00	209.90	558.06	694.40	730.32	4180	46,958	5,233	83
2/23/14 8:00	209.69	558.10	693.87	730.34	4180	46,969	5,227	83
2/23/14 16:00	209.75	557.35	693.87	729.79	4180	46,906	5,242	83
2/24/14 0:00	209.82	557.27	693.80	729.68	4180	46,882	5,243	83
2/24/14 8:00	209.87	557.52	694.04	730.06	4180	46,910	5,246	83
2/24/14 16:00	210.38	558.19	694.83	730.60	4180	46,906	5,248	83
2/25/14 0:00	210.71	558.07	696.80	730.48	4180	46,946	5,258	83
2/24/14 16:00	210.38	558.19	694.83	730.60	4180	46,906	5,248	83
2/25/14 0:00	210.71	558.07	696.80	730.48	4180	46,946	5,258	83
2/25/14 8:00	215.08	557.83	710.80	730.31	4120	46,904	5,294	83
2/25/14 16:00	214.99	557.94	706.73	730.19	4120	46,698	5,284	83
2/26/14 0:00	214.67	558.93	704.24	730.98	4120	46,686	5,261	83
2/26/14 8:00	213.53	559.68	698.67	731.20	4150	46,625	5,248	83
2/26/14 16:00	214.75	560.10	702.20	731.49	4120	46,627	5,233	83
2/27/14 0:00	214.80	559.72	705.52	731.33	4120	46,783	5,244	83
2/27/14 8:00	231.38	561.40	688.09	724.29	3990	42,755	5,181	83
3/2/14 16:00	210.93	559.41	698.83	732.21	4180	47,134	5,263	80
3/3/14 0:00	213.26	560.05	708.37	733.23	4150	47,293	5,288	83
3/3/14 8:00	215.07	559.58	714.58	732.90	4120	47,273	5,303	83
3/3/14 16:00	214.18	560.27	712.44	733.45	4150	47,368	5,309	83
3/4/14 0:00	214.61	560.10	714.06	733.43	4120	47,369	5,287	83
3/4/14 8:00	219.72	561.97	728.20	734.93	4120	47,347	5,384	83
3/4/14 16:00	207.76	560.64	690.80	732.96	4210	47,358	5,196	84
3/5/14 0:00	209.14	559.86	698.19	733.32	4180	47,487	5,233	84
3/5/14 8:00	209.92	561.00	697.93	734.05	4180	47,400	5,231	84
3/5/14 16:00	213.40	562.87	700.03	735.10	4150	46,986	5,238	84
3/6/14 0:00	213.42	562.78	700.08	734.99	4150	46,978	5,238	83
3/6/14 8:00	210.71	559.49	697.14	732.15	4180	47,081	5,252	83
3/6/14 16:00	210.58	559.32	697.21	731.85	4180	47,093	5,247	83
3/7/14 0:00	210.72	559.64	697.45	732.09	4180	47,102	5,245	83
3/7/14 8:00	208.82	557.20	695.87	730.25	4180	47,201	5,238	83
3/7/14 16:00	209.14	557.37	696.28	730.58	4180	47,181	5,249	83
3/8/14 0:00	211.39	556.56	704.82	729.76	4150	47,178	5,275	83
3/8/14 8:00	215.65	556.02	719.05	729.40	4150	47,141	5,392	83
3/8/14 16:00	216.66	556.82	721.16	730.10	4150	47,131	5,406	83
3/9/14 0:00	216.65	556.25	721.59	729.60	4150	47,115	5,413	83
3/9/14 8:00	215.77	555.20	718.80	728.78	4150	47,048	5,408	83
3/9/14 16:00	213.65	557.81	705.98	730.39	4120	46,901	5,262	83
3/10/14 0:00	209.80	558.39	694.49	730.93	4120	47,015	5,161	83
3/10/14 8:00	217.53	556.20	684.32	725.64	4120	44,761	5,276	83
3/10/14 16:00	251.42	552.36	676.58	695.54	4150	36,721	5,092	81
3/11/14 0:00	231.17	558.57	707.98	718.67	4120	43,648	5,283	80
3/11/14 8:00	209.16	546.64	338.91	629.06	4150	17,541	2,555	83
3/11/14 16:00	229.87	522.41	706.95	684.43	4150	40,096	5,550	64
3/12/14 0:00	224.26	543.46	704.40	707.40	4150	43,636	5,427	78
3/12/14 8:00	207.18	561.91	688.91	733.47	4210	47,437	5,148	81

3/12/14 16:00	204.79	562.36	682.11	733.54	4240	47,529	5,110	84
3/13/14 0:00	205.35	564.45	682.10	735.06	4240	47,565	5,088	85
3/13/14 8:00	206.96	567.54	682.56	737.42	4240	47,495	5,080	85
3/13/14 16:00	208.24	566.76	683.68	736.57	4240	47,253	5,116	85
3/14/14 0:00	207.72	566.15	683.74	736.31	4240	47,319	5,119	85
3/14/14 8:00	208.17	566.31	685.57	736.35	4210	47,348	5,089	85
3/14/14 16:00	207.23	565.11	680.36	734.42	4240	47,115	5,091	85
3/15/14 0:00	206.76	564.93	678.18	733.75	4240	47,050	5,067	85
3/15/14 8:00	207.25	564.82	681.55	734.82	4240	47,175	5,115	85
3/15/14 16:00	208.19	564.78	683.25	734.87	4210	47,095	5,104	85
3/16/14 0:00	208.57	564.56	683.70	734.63	4210	47,031	5,115	84
3/16/14 8:00	208.94	564.61	683.80	734.50	4210	46,965	5,118	84
3/16/14 16:00	209.70	565.66	683.60	735.25	4210	46,879	5,118	84
3/17/14 0:00	209.92	565.89	684.08	735.33	4210	46,878	5,117	84
3/17/14 8:00	209.06	566.28	682.35	735.72	4210	46,971	5,093	84
3/17/14 16:00	209.88	566.60	685.80	736.25	4210	47,046	5,116	85
3/18/14 0:00	209.84	566.33	686.10	736.01	4210	47,053	5,119	85
3/18/14 8:00	209.62	566.31	685.18	735.95	4210	47,036	5,113	85
3/18/14 16:00	210.14	566.82	685.89	736.35	4210	47,015	5,117	85
3/19/14 0:00	210.13	566.92	685.76	736.33	4210	47,015	5,112	85
3/19/14 8:00	210.27	567.62	686.03	737.01	4210	47,055	5,109	85
3/19/14 16:00	210.14	567.95	685.74	737.25	4210	47,086	5,101	85
3/20/14 0:00	209.83	567.23	685.59	736.72	4210	47,086	5,105	85
3/20/14 8:00	209.16	566.96	685.48	736.76	4210	47,196	5,100	85
3/20/14 16:00	209.26	567.76	685.33	737.26	4210	47,220	5,087	85
3/21/14 0:00	209.51	568.79	686.40	738.25	4210	47,311	5,083	85
3/21/14 8:00	209.20	567.86	685.72	737.45	4210	47,265	5,087	85
3/21/14 16:00	208.94	566.51	685.90	736.38	4210	47,231	5,101	85
3/22/14 0:00	208.11	566.00	684.68	735.97	4210	47,282	5,088	85
3/22/14 8:00	207.84	565.65	684.44	735.69	4240	47,295	5,123	85
3/22/14 16:00	208.62	566.33	685.62	736.28	4210	47,263	5,097	85
3/23/14 0:00	209.30	567.45	686.82	737.14	4210	47,281	5,096	85
3/23/14 8:00	208.54	563.56	685.34	733.87	4210	47,061	5,130	85
3/23/14 16:00	208.91	562.62	685.05	732.99	4210	46,905	5,149	84
3/24/14 0:00	208.95	563.16	685.55	733.57	4210	46,968	5,146	84
3/24/14 8:00	208.91	562.59	685.58	733.03	4210	46,936	5,151	84
3/24/14 16:00	208.79	562.97	685.67	733.42	4210	46,993	5,145	84
3/25/14 0:00	208.65	562.97	685.81	733.42	4210	47,028	5,142	84
3/25/14 8:00	208.58	562.87	685.52	733.44	4210	47,020	5,145	84
3/25/14 16:00	208.69	563.10	685.63	733.55	4210	47,020	5,142	84
3/26/14 0:00	209.04	564.42	687.32	734.85	4210	47,150	5,138	84
3/26/14 8:00	211.40	565.45	693.51	735.83	4180	47,136	5,148	84
3/26/14 16:00	212.21	565.78	694.82	736.05	4180	47,082	5,162	84
3/27/14 0:00	212.41	565.94	694.92	736.23	4180	47,061	5,166	84
3/27/14 8:00	212.59	566.26	694.62	736.56	4180	47,035	5,168	84
3/27/14 16:00	211.95	566.07	694.38	736.61	4180	47,133	5,161	84
3/28/14 0:00	211.17	566.10	694.52	736.83	4180	47,296	5,148	84
3/28/14 8:00	211.64	566.26	694.72	736.91	4180	47,228	5,155	84
3/28/14 16:00	211.64	566.59	694.57	737.11	4180	47,243	5,148	84

3/29/14 0:00	212.40	567.93	693.91	737.78	4180	47,145	5,135	84
3/29/14 8:00	211.69	567.48	694.09	737.92	4180	47,271	5,139	85
3/29/14 16:00	212.60	567.67	694.59	737.79	4180	47,134	5,150	85
3/30/14 0:00	212.24	567.46	695.48	737.82	4180	47,243	5,150	84
3/30/14 8:00	215.74	569.56	699.07	738.98	4150	46,926	5,151	85
3/30/14 16:00	213.35	567.34	698.57	737.84	4180	47,205	5,183	84
3/31/14 0:00	212.91	567.08	698.76	737.86	4180	47,287	5,183	84
3/31/14 8:00	213.96	561.03	699.66	732.79	4150	46,710	5,254	84
3/31/14 16:00	216.12	566.39	701.45	736.79	4150	46,780	5,217	83
4/1/14 0:00	215.18	566.95	699.81	737.24	4150	46,899	5,186	84
4/1/14 16:00	205.59	543.86	531.97	663.64	4150	35,301	3,655	84
4/2/14 0:00	213.97	554.84	687.53	723.15	4120	45,466	5,169	89
4/2/14 8:00	204.89	549.86	692.58	724.33	4210	47,232	5,285	82
4/2/14 16:00	211.46	563.22	696.75	734.69	4180	47,170	5,202	83
4/3/14 0:00	211.03	563.04	696.85	734.56	4180	47,245	5,195	84
4/3/14 8:00	210.84	562.47	696.88	734.09	4180	47,242	5,198	84
4/3/14 16:00	208.82	552.67	695.26	726.42	4150	46,838	5,262	84
4/4/14 0:00	210.09	549.22	695.29	723.08	4150	46,341	5,329	82
4/4/14 8:00	210.25	548.78	695.21	722.82	4120	46,278	5,304	81
4/4/14 16:00	210.05	548.22	694.89	722.06	4120	46,249	5,299	81
4/5/14 0:00	211.10	554.92	695.32	727.70	4150	46,560	5,269	81
4/5/14 8:00	213.23	561.86	698.82	733.22	4150	46,850	5,217	82
4/5/14 16:00	212.31	563.36	698.75	734.52	4180	47,127	5,213	83
4/6/14 0:00	212.91	564.98	698.82	735.66	4180	47,130	5,198	84
4/6/14 8:00	214.57	566.43	698.97	736.57	4150	46,922	5,172	84
4/6/14 16:00	213.17	565.87	698.81	736.36	4180	47,141	5,191	84
4/7/14 0:00	215.66	569.06	699.52	738.28	4150	46,924	5,147	84
4/7/14 8:00	216.78	570.53	699.31	739.16	4150	48,173	5,295	85
4/7/14 16:00	216.50	569.13	699.39	738.10	4150	46,759	5,160	85
4/8/14 0:00	213.65	567.29	699.22	737.35	4180	47,172	5,177	84
4/8/14 8:00	213.25	567.54	699.16	737.67	4180	47,264	5,168	85
4/8/14 16:00	215.56	565.82	700.95	735.87	4150	46,804	5,199	85
4/9/14 0:00	215.10	567.86	699.66	737.58	4150	46,960	5,160	84
4/9/14 8:00	214.54	568.18	698.03	737.95	4180	46,996	5,182	84
4/9/14 16:00	212.83	568.22	693.76	738.01	4180	47,074	5,141	84
4/10/14 0:00	212.74	568.19	693.35	737.99	4180	47,067	5,139	85
4/10/14 8:00	210.96	568.28	688.45	737.99	4210	47,122	5,130	85
4/10/14 16:00	211.26	568.65	688.47	738.36	4210	47,094	5,134	85
4/10/14 8:00	210.96	568.28	688.45	737.99	4210	47,122	5,130	85
4/10/14 16:00	211.26	568.65	688.47	738.36	4210	47,094	5,134	85
4/11/14 0:00	211.34	568.63	688.82	738.49	4210	47,103	5,140	85
4/11/14 8:00	211.15	568.35	688.31	738.29	4210	47,090	5,140	85
4/11/14 16:00	211.37	567.92	688.06	737.70	4210	46,996	5,145	84
4/12/14 0:00	211.29	567.69	688.23	737.37	4210	47,003	5,142	84
4/12/14 8:00	210.79	568.47	687.70	738.15	4210	47,125	5,123	84
4/12/14 16:00	214.24	569.85	695.24	739.49	4180	47,013	5,156	85
4/13/14 0:00	215.15	570.20	695.94	739.31	4180	46,895	5,159	84
4/13/14 8:00	213.94	568.48	695.06	738.13	4180	46,956	5,161	85
4/13/14 16:00	212.94	566.22	695.32	736.68	4180	47,011	5,181	84

4/14/14 0:00	213.37	566.76	696.23	737.10	4180	47,020	5,183	84
4/14/14 8:00	213.49	566.92	696.71	737.38	4180	47,040	5,188	84
4/14/14 16:00	215.46	567.17	702.70	737.70	4150	47,035	5,198	84
4/15/14 0:00	216.58	568.43	703.74	738.52	4150	46,970	5,201	84
4/15/14 8:00	217.36	569.98	702.82	739.57	4150	46,876	5,191	84
4/15/14 16:00	216.40	568.33	703.00	738.19	4150	46,947	5,191	84
4/16/14 0:00	216.08	567.92	703.26	738.18	4150	47,001	5,199	84
4/16/14 8:00	215.16	567.23	699.89	737.51	4150	46,928	5,183	84
4/16/14 16:00	213.11	567.33	695.66	737.64	4180	47,077	5,171	84
4/17/14 0:00	214.26	568.22	695.94	738.18	4180	46,936	5,180	84
4/17/14 8:00	214.27	567.82	695.86	737.74	4180	46,898	5,183	84
4/17/14 16:00	213.08	566.45	693.81	736.85	4180	46,913	5,180	84
4/18/14 0:00	211.19	567.41	690.52	737.75	4210	47,149	5,162	84
4/18/14 8:00	211.13	567.97	690.31	738.24	4210	47,191	5,153	84
4/18/14 16:00	211.33	568.27	691.01	738.44	4210	47,211	5,152	85
4/19/14 0:00	211.13	568.37	691.12	738.72	4210	47,268	5,152	85
4/19/14 8:00	211.14	567.87	690.97	738.26	4210	47,221	5,158	85
4/19/14 16:00	211.30	567.20	691.38	737.85	4210	47,171	5,175	84
4/20/14 0:00	211.04	567.38	691.23	738.06	4210	47,227	5,168	84
4/20/14 8:00	211.15	566.97	691.44	737.73	4210	47,189	5,177	84
4/20/14 16:00	210.81	566.71	691.29	737.50	4210	47,226	5,172	84
4/21/14 0:00	211.13	566.99	691.68	737.74	4210	47,208	5,176	84
4/21/14 8:00	209.87	566.27	690.98	737.36	4210	47,360	5,162	84
4/21/14 16:00	210.66	566.35	692.34	737.30	4210	47,292	5,176	84
4/22/14 8:00	209.42	565.43	691.57	736.67	4210	47,422	5,162	84
4/22/14 16:00	208.59	564.26	690.97	735.92	4210	47,468	5,164	84
4/23/14 0:00	208.57	564.40	691.34	735.92	4210	47,499	5,159	84
4/23/14 8:00	209.91	564.31	695.45	735.89	4210	47,476	5,194	84
4/23/14 16:00	210.15	563.89	695.75	735.30	4180	47,411	5,162	84
4/24/14 0:00	210.39	564.50	695.95	735.84	4180	47,421	5,160	84
4/24/14 8:00	211.42	566.23	696.70	737.26	4180	47,392	5,161	84
4/24/14 16:00	211.68	567.96	696.24	738.43	4180	47,433	5,136	84
4/25/14 0:00	211.20	567.65	696.17	738.30	4210	47,501	5,169	85
4/25/14 8:00	211.39	566.84	696.79	737.77	4180	47,448	5,152	85
4/25/14 16:00	211.89	566.94	696.94	737.81	4180	47,368	5,161	85
4/26/14 0:00	211.91	567.98	696.90	738.57	4180	47,433	5,145	85
4/26/14 8:00	211.65	568.14	696.84	738.59	4210	47,486	5,170	85
4/26/14 16:00	210.84	566.86	696.25	737.73	4210	47,520	5,174	85
4/27/14 0:00	210.78	567.47	696.41	738.18	4210	47,584	5,162	85
4/27/14 8:00	211.24	567.85	696.76	738.42	4210	47,541	5,166	85
4/27/14 16:00	212.72	568.49	697.79	738.73	4180	47,360	5,150	85
4/28/14 0:00	212.56	568.40	697.80	738.68	4180	47,385	5,148	85
4/28/14 8:00	212.05	568.63	697.55	739.00	4180	47,487	5,136	85
4/28/14 16:00	214.84	570.49	698.78	740.01	4180	48,535	5,313	85
4/29/14 0:00	214.92	570.65	698.79	739.87	4180	48,524	5,304	85
4/29/14 8:00	212.78	569.43	697.88	739.58	4180	47,422	5,140	85
4/29/14 16:00	212.56	569.31	697.43	739.47	4180	47,429	5,136	85
4/30/14 0:00	212.75	569.14	697.56	739.37	4180	47,390	5,144	85
4/30/14 8:00	214.17	568.59	699.12	738.70	4180	47,167	5,180	85

4/30/14 16:00	215.49	569.33	699.33	738.90	4150	46,975	5,151	85
5/1/14 0:00	216.27	569.38	699.81	738.93	4150	46,859	5,169	84
5/1/14 8:00	215.49	568.20	699.34	738.33	4150	46,904	5,178	84
5/1/14 16:00	215.27	568.87	699.01	738.50	4150	46,964	5,152	84
5/2/14 0:00	215.57	569.00	699.13	738.76	4150	46,928	5,162	84
5/2/14 8:00	214.62	568.37	698.81	738.46	4180	47,048	5,192	84
5/2/14 16:00	214.11	568.35	699.59	738.69	4180	47,193	5,187	84
5/3/14 0:00	212.32	566.41	699.05	737.41	4180	47,371	5,181	84
5/3/14 8:00	214.64	568.74	699.75	738.74	4180	47,123	5,187	84
5/3/14 16:00	213.24	566.35	699.46	737.11	4180	47,210	5,196	85
5/4/14 0:00	212.85	566.46	699.22	737.25	4180	47,279	5,186	84
5/4/14 8:00	213.80	567.05	699.41	737.66	4180	47,151	5,199	84
5/4/14 16:00	213.57	566.87	698.45	737.48	4180	47,126	5,195	84
5/5/14 0:00	213.53	566.12	698.47	736.84	4180	47,080	5,204	84
5/5/14 8:00	213.10	565.61	698.86	736.52	4180	47,148	5,204	84
5/5/14 16:00	213.40	566.39	699.67	737.14	4180	47,194	5,200	84
5/6/14 0:00	213.31	565.98	699.96	736.89	4180	47,200	5,206	84
5/6/14 8:00	214.09	566.84	700.51	737.65	4180	47,148	5,214	84
5/6/14 16:00	214.45	567.52	700.95	738.16	4150	47,152	5,175	84
5/7/14 0:00	214.66	567.23	701.44	737.93	4150	47,122	5,184	84
5/7/14 8:00	214.87	567.40	702.00	738.09	4150	47,126	5,187	84
5/7/14 16:00	214.84	567.98	702.04	738.63	4150	47,178	5,180	84
5/8/14 0:00	214.87	568.32	702.16	738.81	4150	47,200	5,173	84
5/8/14 8:00	215.15	565.04	703.13	736.19	4150	46,974	5,229	84
5/8/14 16:00	215.03	567.76	702.90	738.48	4150	47,177	5,189	84
5/9/14 0:00	214.85	567.02	703.13	738.02	4150	47,175	5,199	84
5/9/14 8:00	215.14	567.67	703.61	738.38	4150	47,189	5,192	84
5/9/14 16:00	215.10	566.86	704.02	737.85	4150	47,166	5,206	84
5/10/14 0:00	214.81	567.53	702.37	738.38	4150	47,173	5,189	84
5/10/14 8:00	214.57	566.70	701.59	737.42	4150	47,106	5,187	84
5/10/14 16:00	213.71	563.92	700.56	734.92	4150	47,007	5,199	84
5/11/14 0:00	214.48	564.72	701.91	735.68	4150	47,000	5,210	84
5/11/14 8:00	216.06	568.72	702.93	739.06	4150	47,049	5,193	84
5/11/14 16:00	217.35	569.77	704.21	739.53	4150	46,945	5,198	84
5/12/14 0:00	217.54	569.74	704.16	739.38	4150	46,903	5,199	84
5/12/14 8:00	217.04	569.65	702.07	739.17	4150	46,867	5,184	84
5/12/14 16:00	217.84	569.19	703.65	738.96	4150	46,781	5,215	84
5/13/14 0:00	217.51	568.80	703.31	738.40	4150	46,787	5,205	84
5/13/14 8:00	216.46	567.96	702.53	737.92	4150	46,885	5,198	84
5/13/14 16:00	218.10	569.58	703.58	739.02	4120	46,750	5,170	84
5/14/14 0:00	217.95	570.01	703.57	739.42	4150	46,808	5,199	84
5/14/14 8:00	217.87	570.04	703.23	739.30	4150	46,800	5,193	84
5/14/14 16:00	219.68	570.53	702.32	739.26	4120	47,806	5,330	84
5/15/14 0:00	220.59	570.41	703.02	738.99	4120	47,662	5,348	84
5/15/14 8:00	217.54	567.98	702.66	737.75	4120	46,689	5,181	84
5/15/14 16:00	213.43	566.68	696.74	737.13	4180	47,034	5,189	84
5/16/14 0:00	214.12	565.94	699.27	736.41	4150	46,996	5,175	84
5/16/14 8:00	213.66	563.91	699.73	734.93	4150	46,969	5,198	84
5/16/14 16:00	213.09	568.74	691.43	738.39	4180	46,926	5,139	84

5/17/14 0:00	206.74	567.41	675.52	737.28	4240	47,112	5,075	84
5/17/14 8:00	206.16	566.22	674.11	735.99	4240	47,048	5,068	85
5/17/14 16:00	207.02	568.53	675.22	738.01	4240	47,113	5,061	84
5/18/14 0:00	206.93	569.76	673.98	738.92	4240	47,142	5,038	85
5/18/14 8:00	208.15	569.18	677.36	738.88	4240	47,075	5,089	85
5/18/14 16:00	208.61	567.53	676.05	737.72	4210	46,799	5,092	85
5/19/14 0:00	210.18	570.22	678.96	740.06	4210	46,862	5,097	84
5/19/14 8:00	211.86	568.86	686.96	739.09	4210	46,922	5,161	84
5/19/14 16:00	210.73	566.63	685.52	737.35	4210	46,897	5,168	84
5/20/14 0:00	209.85	566.49	683.84	737.47	4210	46,962	5,155	84
5/20/14 8:00	209.10	564.81	683.98	736.06	4210	46,995	5,160	84
5/20/14 16:00	211.55	565.27	693.38	736.87	4180	47,118	5,190	84
5/21/14 0:00	214.82	565.89	703.25	737.87	4150	47,126	5,238	84
5/21/14 8:00	214.94	564.69	704.32	736.80	4150	47,078	5,255	84
5/21/14 16:00	216.33	566.46	705.52	738.11	4150	47,010	5,259	83
5/22/14 0:00	216.26	565.77	705.93	737.50	4150	46,995	5,266	84
5/22/14 8:00	245.62	561.43	718.00	720.61	4150	40,768	5,430	83
5/22/14 16:00	247.10	560.28	716.13	719.30	4150	40,358	5,468	80
5/23/14 0:00	247.06	559.52	716.09	718.96	4150	40,319	5,488	80
5/23/14 8:00	246.72	559.74	715.28	718.25	4150	40,324	5,448	79
5/23/14 16:00	247.39	560.64	717.29	719.29	4150	40,390	5,458	80
5/24/14 0:00	247.61	561.27	717.84	719.99	4150	40,428	5,460	80
5/24/14 8:00	247.20	560.54	717.70	719.16	4150	40,434	5,454	80
5/24/14 16:00	246.92	560.61	717.45	719.57	4150	40,476	5,459	80
5/25/14 0:00	247.39	560.05	717.80	719.28	4150	40,391	5,483	80

APPENDIX I

HIGH PRESSURE COMPRESSOR PERFORMANCE ANALYSIS

Time	Suction Pressure, Ps [psia]	Suction Temp, Ts [R]	Discharge Pressure, Pd [psia]	Discharge Temp, Td [R]	Volume flowrate [ft3/m]	Polytropic Head [ft.lbf/lbm]	Gas Power (hp)	Efficiency [%]
2/8/14 0:00	699.92	540.29	1,653.47	677.01	2840	32,549	10,350	73
2/8/14 8:00	679.55	547.35	1,670.79	691.22	3050	34,528	11,172	74
2/8/14 16:00	679.90	547.05	1,674.06	691.45	3050	34,566	11,221	74
2/9/14 0:00	679.89	547.61	1,673.97	691.90	3050	34,599	11,203	74
2/9/14 8:00	680.82	548.15	1,675.85	692.37	3050	34,624	11,203	74
2/10/14 0:00	683.12	551.01	1,661.26	694.24	3050	35,111	11,371	74
2/10/14 8:00	683.79	551.79	1,661.88	694.11	3090	35,129	11,449	74
2/10/14 16:00	683.30	552.69	1,665.28	695.07	3090	35,296	11,429	75
2/11/14 0:00	683.95	552.84	1,665.53	695.63	3090	35,276	11,466	74
2/11/14 8:00	684.79	553.13	1,665.62	695.16	3090	35,242	11,419	75
2/11/14 16:00	685.79	553.03	1,668.23	695.42	3120	35,243	11,574	75
2/12/14 0:00	685.65	553.14	1,668.54	695.63	3120	35,265	11,578	75
2/12/14 8:00	685.37	553.50	1,668.59	695.79	3090	35,304	11,441	75
2/12/14 16:00	712.61	550.64	1,673.50	688.31	3360	33,661	12,602	73
2/13/14 0:00	686.07	552.53	1,666.13	694.34	3120	35,141	11,546	75
2/13/14 8:00	685.74	553.26	1,666.12	696.43	3090	35,214	11,516	74
2/13/14 16:00	685.74	553.33	1,666.34	696.05	3090	35,221	11,482	74
2/14/14 0:00	685.86	553.87	1,667.26	696.52	3120	35,269	11,579	74
2/14/14 8:00	686.31	553.81	1,668.00	696.48	3090	35,257	11,479	74
2/14/14 16:00	685.94	553.51	1,667.91	696.33	3090	35,258	11,489	74
2/15/14 0:00	685.84	553.73	1,668.03	696.35	3090	35,280	11,468	75
2/15/14 8:00	686.71	554.21	1,667.56	696.84	3120	35,247	11,586	74
2/15/14 16:00	686.99	554.35	1,667.84	696.32	3120	35,242	11,539	75
2/16/14 0:00	687.76	554.21	1,670.01	696.81	3120	35,245	11,601	74
2/16/14 8:00	687.85	554.85	1,669.90	697.15	3120	35,275	11,568	75
2/16/14 16:00	689.02	554.58	1,672.00	696.71	3120	35,239	11,580	75
2/17/14 0:00	688.03	554.50	1,670.91	697.24	3120	35,269	11,610	74
2/17/14 8:00	688.00	554.55	1,672.06	696.32	3120	35,296	11,537	75
2/17/14 16:00	689.96	554.62	1,671.41	697.03	3090	35,174	11,504	74
2/18/14 0:00	691.16	554.96	1,671.70	696.85	3090	35,129	11,478	75
2/18/14 8:00	690.35	555.08	1,671.82	696.73	3090	35,185	11,445	75
2/18/14 16:00	690.51	555.04	1,671.86	697.53	3090	35,180	11,511	74
2/19/14 0:00	690.54	555.22	1,671.89	697.64	3090	35,190	11,502	74
2/19/14 8:00	690.62	554.92	1,672.16	697.74	3090	35,175	11,539	74
2/19/14 16:00	690.60	554.98	1,671.76	697.46	3090	35,168	11,513	74
2/20/14 0:00	689.95	554.90	1,672.03	696.51	3090	35,202	11,439	75
2/20/14 8:00	689.51	554.05	1,672.18	696.78	3090	35,186	11,531	74
2/20/14 16:00	689.57	554.39	1,672.51	696.83	3090	35,209	11,505	74
2/21/14 0:00	689.88	555.03	1,672.33	697.15	3090	35,224	11,474	75
2/21/14 8:00	690.09	554.81	1,672.41	697.19	3090	35,202	11,500	74

2/21/14 16:00	690.53	555.19	1,671.93	697.14	3090	35,186	11,468	75
2/22/14 0:00	690.66	555.56	1,672.21	697.75	3090	35,209	11,482	75
2/22/14 8:00	690.59	555.51	1,671.93	697.51	3090	35,202	11,467	75
2/22/14 16:00	690.45	555.73	1,672.05	697.79	3120	35,228	11,576	75
2/23/14 0:00	690.35	556.10	1,672.36	698.21	3090	35,264	11,461	75
2/23/14 8:00	689.95	556.46	1,672.16	697.69	3090	35,299	11,382	75
2/23/14 16:00	690.11	555.86	1,672.69	698.39	3090	35,274	11,491	75
2/24/14 0:00	689.99	556.28	1,672.43	698.15	3090	35,296	11,433	75
2/24/14 8:00	690.25	556.53	1,672.98	699.08	3090	35,314	11,483	75
2/24/14 16:00	691.06	556.75	1,672.82	698.24	3090	35,270	11,414	75
2/25/14 0:00	692.84	556.82	1,672.50	697.96	3120	35,160	11,526	75
2/24/14 16:00	691.06	556.75	1,672.82	698.24	3090	35,270	11,414	75
2/25/14 0:00	692.84	556.82	1,672.50	697.96	3120	35,160	11,526	75
2/25/14 8:00	706.33	556.67	1,670.87	695.87	3260	34,323	12,122	74
2/25/14 16:00	702.38	556.98	1,675.69	696.37	3200	34,685	11,842	75
2/26/14 0:00	699.75	557.29	1,665.97	697.09	3200	34,623	11,824	74
2/26/14 8:00	694.12	557.44	1,670.31	698.50	3150	35,071	11,639	75
2/26/14 16:00	697.54	557.21	1,668.92	697.09	3200	34,818	11,796	75
2/27/14 0:00	700.87	557.50	1,667.66	696.58	3200	34,608	11,783	75
2/27/14 8:00	687.35	557.80	1,586.94	693.58	3140	33,390	11,080	74
3/2/14 16:00	694.84	558.22	1,680.59	700.39	3090	35,332	11,498	75
3/3/14 0:00	703.78	560.10	1,672.84	700.12	3200	34,729	11,853	75
3/3/14 8:00	709.93	560.59	1,675.22	698.41	3270	34,450	12,031	75
3/3/14 16:00	707.80	560.41	1,670.43	698.06	3270	34,444	11,985	75
3/4/14 0:00	709.45	560.64	1,676.61	698.50	3270	34,514	12,026	75
3/4/14 16:00	686.90	554.66	1,683.65	698.84	3050	35,660	11,434	75
3/5/14 0:00	694.34	560.56	1,678.69	703.00	3090	35,461	11,466	75
3/5/14 8:00	694.06	560.93	1,678.38	702.76	3090	35,489	11,409	75
3/5/14 16:00	695.92	560.79	1,679.61	703.38	3050	35,406	11,350	75
3/6/14 0:00	695.99	561.19	1,679.54	703.52	3050	35,423	11,325	75
3/6/14 8:00	693.02	557.47	1,678.51	700.01	3090	35,344	11,510	75
3/6/14 16:00	692.93	556.61	1,679.31	698.98	3090	35,314	11,513	75
3/7/14 0:00	693.10	556.94	1,679.23	699.94	3090	35,327	11,556	74
3/7/14 8:00	691.56	554.95	1,678.10	697.35	3140	35,262	11,710	75
3/7/14 16:00	691.80	554.22	1,677.64	696.00	3140	35,188	11,681	75
3/8/14 0:00	700.15	554.06	1,678.50	694.80	3200	34,711	11,969	74
3/8/14 8:00	714.25	554.32	1,692.75	693.55	3260	34,257	12,309	74
3/8/14 16:00	716.29	554.89	1,697.53	694.55	3260	34,292	12,367	74
3/9/14 0:00	716.77	555.33	1,698.36	694.13	3260	34,306	12,296	74
3/9/14 8:00	714.10	555.32	1,689.73	693.55	3260	34,248	12,204	74
3/9/14 16:00	701.29	556.11	1,672.97	695.54	3200	34,629	11,845	75
3/10/14 0:00	690.31	555.12	1,684.62	698.85	3050	35,510	11,450	74
3/10/14 8:00	683.04	553.46	1,630.06	695.18	3050	34,498	11,211	73
3/10/14 16:00	685.51	544.65	1,532.64	671.88	2730	30,675	9,059	74
3/11/14 0:00	705.85	542.59	1,660.77	678.50	2830	32,530	10,305	74
3/11/14 8:00	424.12	542.13	677.28	611.46	2060	18,082	2,468	75
3/11/14 16:00	707.24	529.66	1,647.28	662.37	2760	31,378	10,072	73
3/12/14 0:00	702.67	541.08	1,658.47	677.38	2880	32,560	10,494	73
3/12/14 8:00	685.24	554.47	1,657.20	695.81	3090	35,091	11,349	75

3/12/14 16:00	678.83	554.62	1,636.34	694.73	3050	34,961	11,006	75
3/13/14 0:00	678.72	554.55	1,637.01	695.06	3050	34,983	11,033	75
3/13/14 8:00	678.98	555.15	1,638.73	696.91	3050	35,054	11,117	74
3/13/14 16:00	679.92	554.70	1,639.92	696.84	3050	35,003	11,168	74
3/14/14 0:00	680.06	555.25	1,639.08	696.20	3050	35,000	11,075	75
3/14/14 8:00	681.81	555.89	1,636.57	696.45	3090	34,872	11,207	75
3/14/14 16:00	677.11	551.86	1,643.53	693.86	3030	35,080	11,092	74
3/15/14 0:00	675.05	548.48	1,645.23	690.86	3030	35,036	11,149	74
3/15/14 8:00	678.12	553.64	1,641.63	695.49	3030	35,083	11,065	74
3/15/14 16:00	679.65	554.64	1,638.08	696.04	3030	34,965	11,039	74
3/16/14 0:00	680.02	555.18	1,638.47	695.99	3030	34,982	10,992	75
3/16/14 8:00	680.08	555.08	1,638.75	695.85	3050	34,979	11,065	75
3/16/14 16:00	679.75	554.55	1,640.76	696.07	3030	35,020	11,051	74
3/17/14 0:00	680.24	554.71	1,641.63	696.36	3030	35,023	11,065	74
3/17/14 8:00	678.61	554.95	1,636.15	696.28	3030	34,998	11,011	75
3/17/14 16:00	681.78	555.63	1,645.46	697.07	3070	35,081	11,204	75
3/18/14 0:00	681.98	556.15	1,646.16	697.29	3070	35,117	11,176	75
3/18/14 8:00	681.21	555.95	1,646.10	697.59	3070	35,151	11,203	75
3/18/14 16:00	681.89	556.13	1,645.50	697.69	3070	35,107	11,205	75
3/19/14 0:00	681.78	556.70	1,645.41	698.28	3070	35,146	11,195	75
3/19/14 8:00	682.06	556.50	1,645.13	698.53	3070	35,114	11,235	74
3/19/14 16:00	681.74	556.82	1,645.47	698.48	3070	35,158	11,197	75
3/20/14 0:00	681.62	555.92	1,644.85	697.55	3070	35,094	11,210	75
3/20/14 8:00	681.66	555.90	1,644.26	697.59	3070	35,077	11,214	75
3/20/14 16:00	681.44	556.89	1,644.02	697.80	3070	35,140	11,137	75
3/21/14 0:00	682.50	557.62	1,647.17	698.29	3070	35,198	11,123	75
3/21/14 8:00	681.92	556.28	1,644.86	697.64	3070	35,097	11,188	75
3/21/14 16:00	681.71	556.29	1,645.27	697.22	3070	35,118	11,153	75
3/22/14 0:00	680.47	555.83	1,643.63	697.35	3070	35,126	11,185	75
3/22/14 8:00	680.39	555.88	1,643.16	697.07	3070	35,121	11,159	75
3/22/14 16:00	681.43	555.69	1,646.33	697.56	3070	35,129	11,229	75
3/23/14 0:00	682.65	556.42	1,648.32	698.06	3070	35,149	11,218	75
3/23/14 8:00	681.51	555.54	1,642.06	696.78	3030	35,007	11,040	75
3/23/14 16:00	681.41	555.43	1,638.91	696.61	3030	34,928	11,036	74
3/24/14 0:00	681.91	555.62	1,641.40	696.98	3030	34,973	11,054	74
3/24/14 8:00	681.59	555.60	1,641.51	696.81	3030	34,993	11,038	75
3/24/14 16:00	681.59	556.12	1,642.03	697.04	3030	35,035	11,008	75
3/25/14 0:00	681.72	556.00	1,641.04	696.93	3030	34,996	11,014	75
3/25/14 8:00	681.45	556.16	1,641.01	697.38	3030	35,023	11,026	75
3/25/14 16:00	681.55	556.04	1,641.22	696.90	3030	35,013	11,004	75
3/26/14 0:00	682.78	557.45	1,649.63	699.07	3070	35,237	11,200	75
3/26/14 8:00	688.74	557.52	1,665.48	699.94	3090	35,281	11,430	75
3/26/14 16:00	690.07	557.44	1,669.32	699.33	3090	35,289	11,413	75
3/27/14 0:00	690.26	557.63	1,669.73	700.03	3090	35,302	11,451	75
3/27/14 8:00	689.94	557.88	1,669.81	700.46	3090	35,339	11,454	75
3/27/14 16:00	689.71	557.75	1,669.85	700.30	3090	35,346	11,451	75
3/28/14 0:00	689.92	557.99	1,669.78	700.77	3090	35,348	11,467	75
3/28/14 8:00	690.20	558.38	1,669.16	700.70	3090	35,338	11,430	75
3/28/14 16:00	690.06	558.18	1,669.65	700.62	3090	35,346	11,440	75

3/29/14 0:00	689.19	557.98	1,669.00	700.83	3090	35,372	11,460	75
3/29/14 8:00	689.53	558.99	1,668.23	700.91	3090	35,389	11,378	75
3/29/14 16:00	689.95	558.71	1,668.14	701.30	3090	35,350	11,440	75
3/30/14 0:00	690.95	558.74	1,668.83	701.30	3090	35,309	11,453	75
3/30/14 8:00	694.33	559.24	1,675.54	701.83	3090	35,305	11,501	75
3/30/14 16:00	693.99	558.59	1,674.74	701.53	3090	35,268	11,534	74
3/31/14 0:00	694.19	558.66	1,673.41	701.35	3090	35,227	11,518	74
3/31/14 8:00	695.41	558.36	1,671.97	701.13	3050	35,103	11,400	74
3/31/14 16:00	696.97	559.22	1,672.59	701.34	3050	35,076	11,362	74
4/1/14 0:00	695.31	558.97	1,670.96	701.33	3050	35,119	11,357	74
4/2/14 0:00	683.19	548.57	1,670.11	692.92	3090	35,174	11,652	74
4/2/14 8:00	689.52	554.08	1,669.05	697.81	3090	35,119	11,604	74
4/2/14 16:00	693.20	554.72	1,671.92	698.09	3090	35,011	11,627	74
4/3/14 0:00	693.35	555.08	1,672.36	698.60	3090	35,036	11,634	74
4/3/14 8:00	693.44	555.54	1,672.11	698.17	3090	35,047	11,560	74
4/3/14 16:00	692.30	554.77	1,668.68	697.81	3090	34,986	11,586	74
4/4/14 0:00	692.57	554.75	1,665.39	697.34	3050	34,887	11,408	74
4/4/14 8:00	692.50	554.80	1,664.82	697.42	3050	34,880	11,408	74
4/4/14 16:00	692.17	554.53	1,664.62	697.07	3050	34,878	11,401	74
4/5/14 0:00	692.26	554.91	1,667.31	697.80	3050	34,963	11,423	74
4/5/14 8:00	695.37	555.45	1,674.76	698.35	3090	34,995	11,614	74
4/5/14 16:00	695.41	554.97	1,676.49	697.64	3090	35,003	11,607	74
4/6/14 0:00	695.35	555.66	1,676.41	698.30	3090	35,047	11,590	74
4/6/14 8:00	695.14	555.76	1,677.57	698.46	3090	35,094	11,590	74
4/6/14 16:00	695.21	556.06	1,675.78	698.44	3090	35,063	11,561	74
4/7/14 0:00	695.90	556.43	1,676.10	699.54	3090	35,058	11,619	74
4/7/14 8:00	695.46	556.62	1,675.53	699.61	3090	35,081	11,600	74
4/7/14 16:00	695.57	556.50	1,675.99	699.54	3050	35,078	11,458	74
4/8/14 0:00	695.72	556.59	1,675.84	699.65	3090	35,072	11,610	74
4/8/14 8:00	695.75	556.79	1,675.17	699.32	3090	35,063	11,567	74
4/8/14 16:00	697.48	556.55	1,676.44	698.50	3090	34,975	11,557	74
4/9/14 0:00	696.10	556.03	1,678.16	698.78	3050	35,069	11,454	74
4/9/14 8:00	694.49	557.09	1,673.46	699.36	3050	35,111	11,372	74
4/9/14 16:00	690.29	556.54	1,662.71	699.81	3050	35,068	11,387	74
4/10/14 0:00	689.80	556.54	1,661.92	699.32	3050	35,075	11,343	74
4/10/14 8:00	684.86	557.29	1,650.41	699.85	3050	35,129	11,232	74
4/10/14 16:00	684.81	557.27	1,650.04	700.20	3050	35,124	11,258	74
4/10/14 8:00	684.86	557.29	1,650.41	699.85	3050	35,129	11,232	74
4/10/14 16:00	684.81	557.27	1,650.04	700.20	3050	35,124	11,258	74
4/11/14 0:00	685.23	557.76	1,649.99	700.59	3050	35,128	11,249	74
4/11/14 8:00	685.12	556.96	1,644.36	699.56	3020	34,946	11,133	74
4/11/14 16:00	685.00	556.43	1,641.35	698.41	3020	34,843	11,097	74
4/12/14 0:00	685.18	556.64	1,642.05	698.46	3020	34,861	11,085	74
4/12/14 8:00	684.78	557.15	1,640.97	699.00	3020	34,890	11,071	74
4/12/14 16:00	691.74	557.50	1,663.68	700.52	3050	35,065	11,374	74
4/13/14 0:00	692.38	557.38	1,664.03	700.15	3050	35,028	11,368	74
4/13/14 8:00	691.69	557.46	1,662.23	699.46	3050	35,024	11,299	74
4/13/14 16:00	692.12	556.64	1,660.80	699.49	3050	34,919	11,384	74
4/14/14 0:00	692.99	557.43	1,662.93	699.65	3050	34,964	11,337	74

4/14/14 8:00	693.48	557.25	1,663.50	699.90	3050	34,942	11,380	74
4/14/14 16:00	699.39	558.16	1,677.18	700.15	3050	34,982	11,410	74
4/15/14 0:00	700.39	558.57	1,679.06	701.08	3050	34,997	11,458	74
4/15/14 8:00	699.32	558.83	1,676.77	701.21	3050	35,019	11,425	74
4/15/14 16:00	699.50	558.52	1,676.99	701.09	3050	34,996	11,449	74
4/16/14 0:00	699.94	558.39	1,675.93	700.54	3050	34,934	11,427	74
4/16/14 8:00	696.74	558.50	1,664.48	700.14	3050	34,846	11,335	74
4/16/14 16:00	692.49	558.71	1,654.90	699.92	3050	34,870	11,230	74
4/17/14 0:00	692.62	559.24	1,654.68	701.20	3020	34,894	11,167	74
4/17/14 8:00	692.71	558.55	1,654.60	701.14	3020	34,849	11,226	74
4/17/14 16:00	690.69	558.52	1,650.02	700.21	3020	34,847	11,129	74
4/18/14 0:00	687.54	558.49	1,644.23	700.96	3020	34,893	11,135	74
4/18/14 8:00	687.33	559.20	1,644.42	700.84	3030	34,948	11,096	74
4/18/14 16:00	687.85	558.43	1,644.61	700.98	3030	34,881	11,184	74
4/19/14 0:00	687.83	558.95	1,643.85	701.10	3030	34,893	11,145	74
4/19/14 8:00	687.74	558.59	1,643.27	700.89	3030	34,862	11,161	74
4/19/14 16:00	688.19	559.07	1,643.20	701.32	3030	34,863	11,156	74
4/20/14 0:00	688.05	559.04	1,642.79	701.54	3030	34,861	11,171	74
4/20/14 8:00	688.29	558.81	1,642.70	701.73	3030	34,834	11,211	73
4/20/14 16:00	688.15	558.77	1,642.36	700.40	3030	34,823	11,115	74
4/21/14 0:00	688.58	558.87	1,641.69	701.47	3030	34,793	11,191	73
4/21/14 8:00	687.89	558.67	1,641.28	701.49	3030	34,813	11,199	73
4/21/14 16:00	689.28	558.70	1,642.91	700.86	3020	34,769	11,137	74
4/22/14 0:00	689.36	557.68	1,643.92	700.58	3020	34,732	11,210	73
4/22/14 8:00	688.55	557.35	1,643.63	699.83	3020	34,749	11,173	73
4/22/14 16:00	688.00	557.05	1,644.01	699.68	3020	34,774	11,181	73
4/23/14 0:00	688.32	557.05	1,645.07	700.20	3020	34,784	11,223	73
4/23/14 8:00	692.40	556.30	1,655.59	699.13	3050	34,755	11,393	73
4/23/14 16:00	692.68	555.74	1,655.72	698.87	3050	34,710	11,430	73
4/24/14 0:00	692.90	555.93	1,654.99	699.52	3010	34,694	11,313	73
4/24/14 8:00	693.61	556.73	1,655.11	699.41	3010	34,698	11,244	73
4/24/14 16:00	693.07	556.70	1,654.78	699.17	3010	34,719	11,220	73
4/25/14 0:00	693.02	557.05	1,654.59	699.47	3010	34,738	11,210	73
4/25/14 8:00	693.66	556.86	1,654.22	699.56	3010	34,682	11,244	73
4/25/14 16:00	693.88	557.02	1,654.92	699.20	3010	34,693	11,206	73
4/26/14 0:00	693.80	556.85	1,654.06	699.24	3010	34,667	11,223	73
4/26/14 8:00	693.71	556.76	1,654.01	700.02	3010	34,672	11,286	73
4/26/14 16:00	693.14	556.18	1,653.42	699.41	3010	34,654	11,286	73
4/27/14 0:00	692.57	556.71	1,653.00	699.46	3010	34,707	11,232	73
4/27/14 8:00	692.91	556.35	1,652.88	699.67	3010	34,666	11,286	73
4/27/14 16:00	693.87	556.26	1,651.94	699.41	3010	34,581	11,290	73
4/28/14 0:00	693.92	556.71	1,652.53	699.59	3010	34,618	11,263	73
4/28/14 8:00	693.57	556.86	1,652.28	699.39	3010	34,639	11,230	73
4/28/14 16:00	694.68	557.10	1,652.33	700.23	3010	34,594	11,286	73
4/29/14 0:00	694.71	557.09	1,652.21	700.03	3010	34,588	11,273	73
4/29/14 8:00	693.99	556.97	1,651.20	699.84	3010	34,597	11,259	73
4/29/14 16:00	693.65	557.11	1,650.55	699.78	3010	34,608	11,236	73
4/30/14 0:00	693.72	557.10	1,650.54	699.98	3010	34,605	11,253	73
4/30/14 8:00	695.37	556.39	1,651.20	699.16	3010	34,481	11,284	73

4/30/14 16:00	695.34	556.96	1,651.60	699.79	3000	34,528	11,240	73
5/1/14 0:00	695.76	556.70	1,651.29	700.01	3000	34,483	11,287	72
5/1/14 8:00	695.35	556.35	1,650.79	699.67	3000	34,473	11,287	72
5/1/14 16:00	695.08	556.41	1,650.53	698.41	3000	34,478	11,187	73
5/2/14 0:00	695.17	556.45	1,649.95	699.12	3000	34,465	11,236	73
5/2/14 8:00	694.90	556.24	1,651.11	699.03	3000	34,497	11,244	73
5/2/14 16:00	695.72	556.47	1,652.71	699.81	3000	34,506	11,292	73
5/3/14 0:00	695.35	556.51	1,652.32	699.66	3000	34,519	11,272	73
5/3/14 8:00	695.90	556.39	1,654.54	699.50	2990	34,534	11,243	73
5/3/14 16:00	695.82	556.52	1,653.87	698.82	2990	34,525	11,181	73
5/4/14 0:00	695.55	556.43	1,652.85	699.08	3000	34,513	11,241	73
5/4/14 8:00	695.72	556.50	1,652.24	699.01	2970	34,491	11,119	73
5/4/14 16:00	694.73	556.55	1,650.56	699.27	2970	34,512	11,118	73
5/5/14 0:00	694.76	556.34	1,650.09	699.25	2970	34,487	11,136	73
5/5/14 8:00	695.13	556.05	1,650.44	698.74	3000	34,456	11,243	73
5/5/14 16:00	695.88	556.46	1,651.96	699.41	3000	34,476	11,266	73
5/6/14 0:00	696.16	556.57	1,652.16	698.79	3000	34,466	11,216	73
5/6/14 8:00	696.77	557.18	1,652.30	699.47	3000	34,472	11,220	73
5/6/14 16:00	697.22	557.42	1,652.18	700.75	3000	34,463	11,298	72
5/7/14 0:00	697.71	558.02	1,652.02	700.38	3000	34,461	11,224	73
5/7/14 8:00	698.24	558.62	1,651.40	700.74	3000	34,450	11,205	73
5/7/14 16:00	698.22	558.85	1,651.48	700.59	3000	34,465	11,172	73
5/8/14 0:00	698.32	558.55	1,651.53	701.05	3000	34,447	11,234	73
5/8/14 8:00	699.55	558.23	1,651.16	700.08	3010	34,343	11,250	73
5/8/14 16:00	699.12	558.93	1,650.99	701.43	3000	34,410	11,240	73
5/9/14 0:00	699.36	558.99	1,650.67	700.69	3000	34,387	11,184	73
5/9/14 8:00	699.84	558.84	1,652.64	701.02	3000	34,401	11,230	73
5/9/14 16:00	700.32	559.11	1,653.74	701.41	3010	34,418	11,279	73
5/10/14 0:00	698.59	558.69	1,650.71	700.22	3010	34,413	11,203	73
5/10/14 8:00	697.91	557.93	1,651.25	700.32	3010	34,426	11,269	73
5/10/14 16:00	696.73	558.61	1,647.63	701.37	3010	34,449	11,264	73
5/11/14 0:00	698.17	558.55	1,647.92	700.32	3010	34,362	11,216	73
5/11/14 8:00	699.13	558.42	1,650.06	701.50	3010	34,360	11,329	72
5/11/14 16:00	700.30	558.45	1,650.47	700.98	3010	34,301	11,307	72
5/12/14 0:00	700.21	558.23	1,650.49	701.10	3010	34,295	11,335	72
5/12/14 8:00	698.19	557.97	1,650.59	700.86	3010	34,399	11,309	72
5/12/14 16:00	699.85	558.06	1,650.60	700.42	3010	34,305	11,295	73
5/13/14 0:00	699.54	557.87	1,651.05	700.45	3010	34,324	11,310	72
5/13/14 8:00	698.81	557.39	1,650.61	699.83	3010	34,326	11,297	73
5/13/14 16:00	699.71	558.07	1,651.05	700.16	3010	34,323	11,273	73
5/14/14 0:00	699.72	557.97	1,650.56	700.20	3010	34,305	11,285	73
5/14/14 8:00	699.42	557.60	1,650.89	699.68	3010	34,308	11,276	73
5/14/14 16:00	698.18	557.95	1,647.22	700.63	3000	34,314	11,256	72
5/15/14 0:00	698.68	557.84	1,646.91	699.68	3000	34,266	11,205	73
5/15/14 8:00	698.76	557.20	1,645.60	699.29	3000	34,193	11,236	72
5/15/14 16:00	693.02	557.16	1,637.42	699.84	3000	34,325	11,188	72
5/16/14 0:00	695.69	557.10	1,642.55	699.46	3000	34,291	11,209	73
5/16/14 8:00	696.22	556.15	1,648.38	699.19	3000	34,350	11,284	72
5/16/14 16:00	687.53	557.18	1,626.32	699.57	3000	34,371	11,078	73

5/17/14 0:00	671.57	557.25	1,589.18	699.77	2980	34,392	10,757	73
5/17/14 8:00	670.15	556.53	1,588.16	698.44	2980	34,404	10,704	73
5/17/14 16:00	671.12	556.75	1,587.95	699.26	2980	34,358	10,757	73
5/18/14 0:00	669.73	557.23	1,584.68	699.26	2980	34,384	10,693	73
5/18/14 8:00	673.20	559.73	1,592.26	701.30	2980	34,515	10,673	73
5/18/14 16:00	671.93	561.63	1,582.87	703.43	2950	34,468	10,527	73
5/19/14 0:00	674.80	563.59	1,586.51	705.42	2950	34,505	10,541	73
5/19/14 8:00	683.06	562.01	1,605.62	704.46	2930	34,406	10,667	73
5/19/14 16:00	681.61	562.41	1,603.19	704.49	2930	34,453	10,613	73
5/20/14 0:00	680.08	562.77	1,596.62	704.33	2980	34,396	10,726	73
5/20/14 8:00	680.05	562.31	1,596.96	703.36	2980	34,376	10,699	73
5/20/14 16:00	689.53	563.83	1,620.46	704.79	2950	34,497	10,706	74
5/21/14 0:00	699.47	564.53	1,643.52	706.52	2950	34,537	10,921	73
5/21/14 8:00	700.58	563.93	1,648.78	706.35	2950	34,570	10,979	73
5/21/14 16:00	701.68	564.36	1,648.32	705.86	3000	34,515	11,108	73
5/22/14 0:00	702.04	564.47	1,647.72	705.04	3000	34,480	11,045	74
5/22/14 8:00	710.13	554.96	1,671.77	696.49	3090	34,040	11,762	72
5/22/14 16:00	707.99	553.82	1,671.84	695.87	3090	34,098	11,789	72
5/23/14 0:00	708.01	553.33	1,674.33	695.61	3090	34,129	11,816	72
5/23/14 8:00	707.24	553.11	1,673.09	695.33	3090	34,129	11,804	72
5/23/14 16:00	709.34	554.94	1,673.82	696.96	3090	34,136	11,788	72
5/24/14 0:00	710.00	555.40	1,674.79	697.10	3050	34,148	11,613	73
5/24/14 8:00	709.80	555.56	1,673.34	697.71	3050	34,137	11,640	72
5/24/14 16:00	709.59	556.05	1,671.98	698.57	3050	34,147	11,655	72
5/25/14 0:00	709.95	556.02	1,672.86	698.82	3050	34,148	11,683	72