POTENTIAL APPLICATION OF COILED TUBING DRILLING IN MALAY BASIN

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CERTIFICATION OF APPROVAL

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CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

MUHAMMAD ZAWAWI BIN HAJI ZAIDI

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ABSTRACT

Coiled Tubing Drilling (CTD) is a niche technology developed in continuous effort to recover hydrocarbon from subsurface. It had been applied around the world and show significant advantages compare to the conventional drilling. One of the significant advantages is increase in the rate of penetration (ROP) which is higher compare to the conventional one.

In this project, Bourgoyne and Young ROP model have been selected to study the effects of several parameters during drilling operation. Important parameters such as depth, pore pressure, equivalent circulating density, bit weight, rotary speed, bit tooth wear, and jet impact force are extracted from drilling report. In order to study their relationship statistical method which is multiple regressions analysis has been used. The penetration model for the conventional and CTD wellare constructed using the results of statistical method. In the end, the result from analysis being compared to determine the CTD advantage over the conventional well in term of higher rate of penetration value.

Overall, this project provides a study to the most complete mathematical model for rate of penetration that was constructed by Bourgoyne and Young. The model had been chose before other existed model. Using the Bourgoyne and Young model, CTD ROP is calculated. Several assumptions have been made. The ROP value we get from the model show us the potential of CTD to be applied in Malay Basin.

TABLE OF CONTENTS

LIST OF FIGURE

LIST OF TABLE

Abbreviations

Symbol		Unit, Field (SI)
BHA	Bottom Hole Assembly	-
ECD	Equivalent Circulating Density	[M/L3], ppg (sg)
MD	Measured Depth	[L], ft(m)
MW	Mud Weight (Density)	[M/L3], PPg (sg)
Opt	Optimum	-
PDC	Polycrystalline Diamond Cutter	-
PPFG	Pore Pressure Fracture Gradient	-
ROP	Rate Of Penetration	[L/T], ft/hr (m/hr)
RPM	Revolution Per Minute	[T-1], rpm (-)
TD	Total Depth	[L], ft(m)
TVD	True Vertical Depth	[L], ft(m)
WOB	Weight On Bit	[ML/T2], 1000 LBF
CTD	Coiled Tubing Drilling	-

CHAPTER 1

INTRODUCTION

1.1 BACKGROUND OF STUDY

This is the first time coiled tubing drilling (CTD) being applied in Malay Basin. In other part of the world, it has been widely used. In the earlier stage, coiled tubing has been used only in well cleaning, workover and also well logging. But in the early 90's, the industry are having the benefits from the coiled tubing (CT) application in drilling activities.

As of Malay Basin, the intention was to evaluate the capabilities of CTD and its potential for use in the basin. To continue maximizing and optimizing of oil recovery from the reservoir, CTD is a very favourite choice, especially for the mature fields. The advantages of CTD seem interesting and efficient to be applied. It will be a great learning experience. The result will incorporated into field redevelopment plan for fields in the basin.

Major drilling variables considered to have an effect on drilling rate of penetration are not fully comprehend and complex to model. There are many proposed mathematical models which attempted to combine known relations of drilling parameters. The proposed models worked to optimize drilling operation by mean of selecting the best bit weight and rotary speed to achieve minimum cost. Considerable drilling cost reductions have been achieved by means of using the available mathematical models.

1.2 PROBLEM STATEMENT

Although there are many benefits of CTD have been cited in this document, it still has limitations. The aspects which have to be managed and observe properly to make sure the project will be fluent and successful.

It is very important to understand the relationship between important parameters during drilling. Though it is very hard to provide the relationship of all parameters but with proper application of mathematical method estimation could be predicted those at least can be the guide for planning optimization of drilling operation.

Drilling parameters that is considered throughout this study include formation strength and bit type, formation depth, pore pressure, equivalent circulating density, bit weight, rotary speed, bit tooth wear and jet impact force. Other effects of drilling variables such as mud type, solid content are also included in term of formation strength and bit type.

The benefit of statistical method is the ability of being able to estimate the rate of penetration as a function of independent drilling parameters. Following the analysis of the drilling parameters, a relation between drilling parameters and rate of penetration could be determined.

For that reasons, the ability to relate many drilling parameters and the possibility to analyze it with mathematical methods provide the best ways to optimize drilling operation.

1.3 OBJECTIVE

The objectives of this research are:

1. To determine the CTD ROP value using suitable mathematical model.
2. To compare ROP model of CTD and conventional drilling in Malay Basin.

1.4 SCOPE OF STUDY

This study intention is to choose the suitable ROP model for CTD project in Malay Basin. Existing ROP model will be used to construct the ROP model. The project will concentrate on analyze and extract data from the drilling report to obtain variables x_1 until x_8 for each data point. Statistical analysis which is multiple regressions will be applied to the variables to determine the constants of a_1 until a_8 that represent the formation. The constant coefficient will be used to predict rate of penetration for the CTD and conventional well. Then, the model for the CTD and conventional well be constructed and rate of penetration will be predicted. Next, the model for conventional and CTD well will be compare.

CHAPTER 2

THEORY AND LITERATURE REVIEW

2.1 Malay Basin

Six major Tertiary sedimentary basins are present in Malaysia: the Malay, Penyu, Sarawak, Sabah, Sandakan and a portion of Tarakan basins [1]. Of these basins, only the Malay, Sarawak; and Sabah basins have been proven to contain significant oil and gas accumulations, with a total in-place of 20 billion barrels of oil and 130 tcf of gas. Marginal oil and gas accumulations have been found in the Penyu and Sandakan basins. Very limited exploration has been conducted in the Malaysia sector of the Tarakan basin, and consequently its hydrocarbon potential has not been established.

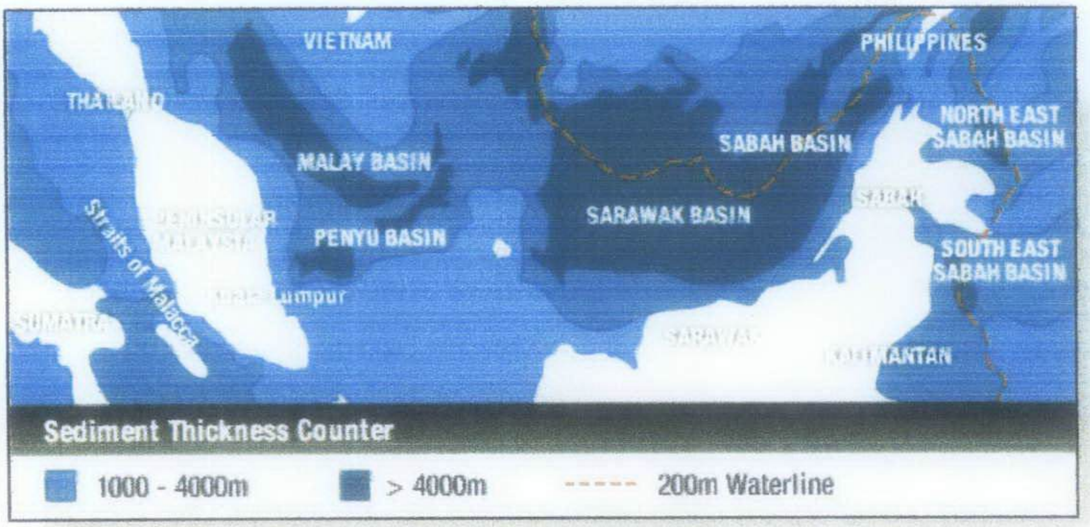

Figure 1: Sedimentary Basin of Malaysia [1]

The Malay, Penyu, and West Natuna (Indonesia) basins are believed to have been formed as a result of upward buckling of the Sunda landmass in Late Cretaceous. Subsequent collapse of this landmass along the northwest and east-northeast and westerly directions resulted in formation three depocenters: the Malay, Penyu and West

Natuna basins. High heat flow observed in both the Malay and Penyu basins provides strong evidence that the basins were formed by crustal splitting and rifting.

The rate during Tertiary of rifting and basin development, which varied with different depocenters, appears to have been higher in the Malay basin than in the Penyu and West Natuna basins; correspondingly, the Malay basin received more sediments than the others. A basement reflector has not been recognized in the seismic data acquired in the Malay basin, and its absence has led to the belief that the basin contains sediments at least 15 km thick. In contrast, a basement reflector is easily traceable throughout the Penyu basin, with sediment thickness of about 7 km (4-second TWT) in the deepest part of the basin.

The sediments penetrated by exploration drilling in the basins indicate that the oldest sequence encountered is Oligocene [2]. These Oligocene and lower Miocone sequences were deposited in relatively enclosed lacustrine environments, and only toward middle early Miocene were marine conditions dominant. Much of the sediment input was primarily terrigenous. During Oligocene, the environments were markedly seasonal and non-seasonal (overwet) with swamp conditions predominated only during late early Miocene to late middle Miocene.

Both the basins experienced one major tectonic episode in the Miocene-Pliocene and most of the known hydrocarbons were found trapped within the structures formed during this period.

The Malay Basin is approximately 83,000 km^2. The basin is approximately 500 km long and 200 km wide. Robinson (1985) estimated the volume of Tertiary sediments in the Malaysian portion of the basin at 338,000 km^3 with more than 9,150 m of Tertiary sediments in some areas. However, more recent estimates suggest that more than 12 km of Oligocene and post-Oligocene sediments have filled the basin (Tjia, 1994; Ngah and others, 1996). The Malay Basin trends northwest to southeast running almost perpendicular to the east/west trending Penyu Basin and the northeast/southwest trending West Natuna basins on its south and bends north/south at its northern end to parallel the Pattani Basin in the Gulf of Thailand (Hutchison, 1996).

Since the first offshore exploration 1957, hundreds to thousands of wells had been drilled in the Malay Basin. There are many types of well existed and being used here. It is crucial to have the new and suitable technology in achieving efficient cost project while producing the hydrocarbon. In the hope of this CTD application can open new path to more efficient project, we will see many well will be drilled using this technique.

2.2 Coiled Tubing Drilling (CTD)

Coiled tubing (CT) is a continuous string of tubing stored on a reel, which can be run into dead or pressurized well [4]. Running in and out of a pressurized well is made possible by the use of a pack-off (stuffing box) that seals around the coil. The injector head provides the axial forces to snub and retrieve the CT in and out of the well. Since the introduction of CT, it has been used for numerous well services activities, such as well stimulations, milling, well clean-ups and sand clean-out. CT capabilities for conveying equipment, electricity and fluids downhole have resulted in CT setting the standard for well service operations.

The coiled tubing unit is comprised of the complete set of equipment necessary to perform standard continuous-length tubing operations in the field. The unit consists of four basic elements [3]:

1. Reel - for storage and transport of the CT
2. Injector Head - to provide the surface drive force to run and retrieve the CT
3. Control Cabin - from which the equipment operator monitors and controls the CT
4. Power Pack - to generate hydraulic and pneumatic power required to operate the CT unit

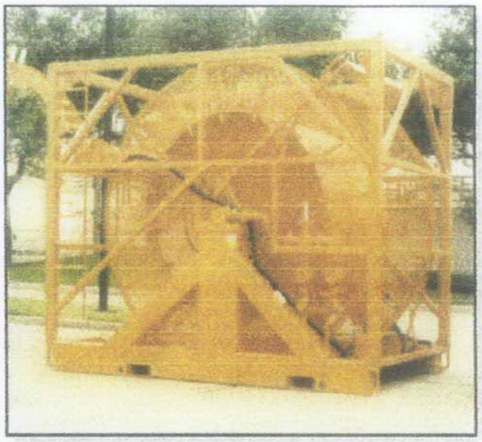

Figure 2: Injector Head [3]

Figure 3: Reel [3]

Figure 4: Control Cabin [3]

Figure 5: Power Pack [3]

Figure 6: CT Operations on an Offshore Platform [3]

Advances in technology made in the late 80's have triggered this wave of CT activity. These advances improved the reliability and effectiveness of CT services. The primary technology advancements that triggered this wave were [4]

- Improvements in CT pipe manufacturing – Increased lengths of the continuous strips of material that pipe is made from were first produced in 1983. These longer strip lengths decreased the number of welds in a string of CT. since welds are major source of failure in CT pipe, decreasing the number of welds improved the reliability of the pipe. New welding methods were developed, with the most notable being the strip biased welds in a place of tube to tube butt welds. These biased strip welds, introduced in 1989, are much more reliable than butt welds.
- Improved methods of predicting pipe life and limits – The life of CT pipe is governed primarily by the fatigue damage caused when pipe is bent over the reel and the guide arch. Models were developed to predict the fatigue life of the CT to ensure that the pipe was scrapped before it reaches the end of its life and a failure occurred.
- Larger pipe sizes – Previously 1 inch and 1.25 inch CT had been used. In 1985, the first 1.5 inch CT was developed, and in 1986 the first 1.75 inch CT was developed. These larger sizes (considered medium size today!) greatly increased the capabilities of CT services.
- CT Logging – The technology required to use CT to push conventional electric line logging tools into horizontal wells was developed in the late 80's. though this type of services was limited by the size of the horizontal well market and by high cost, it was the first step toward real time downhole communications with CT.
- Improvements in CT equipment – Many improvements were made to the CT units and monitoring equipment in the late 80's. The first real time CT pipe monitoring device was developed.

At the same time as these technical advancements were being made, economic and environmental demands on oil industry increased. CT services were often more economical and environmental friendly than similar services performed with a rig or snubbing unit. CT training efforts were increased to raise the service level performance. These force combined to increase the acceptance of CT services by the oil and gas industry which allowed the wave to grow.

In the continual search for better tools to recover hydrocarbons from the ground, the drilling industry has developed numerous niche technologies to tackle unique reservoir challenges. One of the technologies is coiled tubing drilling (CTD) [4].

In general, CTD can be divided into two main categories consisting of directional and non-directional wells. Non-directional wells use a fairly conventional drilling assembly in conjunction with a downhole motor. Directional drilling requires the use of an orienting device to steer the well trajectory, per the well plan. CTD can then be further segmented into over-balance and under-balanced drilling applications.

Bit design and selection for CTD follows the same theory as is used in conventional rotary drilling. However, CTD generally uses higher bit speeds at lower weight bit as a result of the structural differences in CT versus jointed pipe [5].

CTD advantages such as faster mobilization/demobilization, faster trip times, continuous circulation during tripping, smaller footprint, less site preparation/remediation, dog-leg severity capability and also continuous downhole data acquisition are making its market growing faster and wider along the way[6].

The live well intervention capabilities of CT have made it an ideal tool for underbalanced drilling in damage-sensitive formations. Although rotary drilling rigs have been doing this for years, the lack of pipe connections on CT can provide better control of bottomhole pressure and safer work environment in some circumstances.

Sidetracking existing wells is another CTD application [7]. A common workover operation is to pull the existing completion tools, mill through the casing or liner, and sidetrack the well, then complete the well with new completion tools. If such a sidetrack could be performed without the need to pull or rerun the existing tubing, significant time and cost savings may be possible, thereby improving the overall economics of such wells.

Since the early 1990s, increased interest in production improvements has resulted in the planning of re-entry activities. This was made possible by continuously downsizing drilling bits and bottomhole assemblies. In addition to the ability to drill through $4^{1/2}$-in. and larger production tubing, new techniques and newly developed tools made it possible for the technology to be applied in well completed with $3^{1/2}$-in. tubing.

Specialized bottomhole assemblies (BHA) have been developed to meet the specific drilling environments and geometries associate with CT underbalanced drilling and trough tubing sidetracking.

By exploiting the advantages, CTD had been applied in re-entries well (horizontal sidetracks), shallow gas, directional drilling (multilateral wellbores), balanced directional drilling (low pressure mature reservoir), underbalanced drilling, overbalanced drilling (reduces required mud weight) and also grass roots well. With continuous learning, research and designing, we can see in the future CTD will play major part in oil and gas industry.

2.3 Rate Of Penetration (ROP) Model

Rate of penetration (ROP) is the speed at which the drill bit can break the rock under it and thus deepen the wellbore. This speed is usually reported in units of feet per hour or meters per hour [9].

In the recent years, drilling optimization techniques have been used to reduce drilling operation cost. This would be done by reducing the operation time, since time always money in drilling operations. The concept of time taking for any drilling operation can be stated in term of drilling rate of penetration [10]. Therefore, estimation of penetration rate is one of the essential parts of drilling optimization.

One of the most important early studies performed in regards to the optimal drilling detection was by Bourgoyne and Young [12]. They constructed a linear penetration rate model and performed a multiple regression analysis of drilling data in order to select bit weight, rotary speed, and bit hydraulics. In their analysis they included the effects of formation strength, formation depth, formation compaction, pressure differential across the hole bottom, bit diameter, bit weight, rotary speed, bit wear and bit hydraulics. They found that regression analysis procedure can be used to systematically evaluate many of the constants in the penetration rate equation.

Maurer [13] derived rate of penetration equation for roller-cone type of bits considering the rock cratering mechanisms. The equation was based on "perfect cleaning" condition where all of the rock debris is considered to be removed between tooth impacts. A working relation between drilling rate, weight on bit and string speed was achieved assuming that the hole was subject perfect hole cleaning circumstances. It was also mentioned that the obtained relationships were a function of drilling depth.

Bingham [14] proposed a rate of penetration equation based on laboratory data. In their equation the threshold bit weight was assumed to be negligible and rate of penetration was a function of applied weight on bit and rotary speed of string.

Young [15] performed development of onsite computer system to control bit weight and rotary speed. He introduced a minimum cost drilling terminology with four main equations; drilling rate as a function of weight on bit and bit tooth height, bit wearing rate as a function of bit rotation speed, bit tooth wear rate and finally drilling cost. By integration of the introduced equations for the optimum weight on bit and rotary speed constants the best solutions are reported to be obtained.

Al-Betairi et al. [16] presented a case study for optimizing drilling operations in the Arabian Gulf area. The drilling model proposed by Bourgoyne and Young [17] was applied in their model with Statistical Analysis System was validated. They observed that for particular set of coefficients of the model was observed to be inversely proportional to the influence of that parameter on the rate of penetration. The more the data points the reliable estimated drilling parameters became.

Warren [18] presented an ROP model that includes the effect of both the initial chip generation and cuttings-removal process. The rate of penetration equation they derived is formed of two terms, working only with perfect hole cleaning assumption. The first term defined the maximum rate supporting the WOB effect without tooth penetration rate, the second term on the other hand considering tooth penetration into the formation. The equation was found to fit the experimental data for both steel tooth and insert bit types.

2.4 Bourgoyne and Youngs' Rate of Penetration Model

Bourgoyne and Youngs [12] method is the most important drilling optimization method since it is based on statistical synthesis of the past drilling parameters. A linear penetration model is being introduced and multiple regression analysis over introduced rate of penetration equation is being conducted. For that reason this method is considered to be the most suitable method determine the ROP value..

The model proposed by Bourgoyne and Young [12] has been adopted for this project in order to derive equations to perform the ROP estimation using the available input data. This model has been selected because it is considered as one of the complete mathematical drilling models in use of the industry for roller-cone type of bits.

Equation 2.1 gives the linear rate of penetration equation which is a function of both controllable and uncontrollable drilling variables. When the multiple regression process is performed the model has been modified based on controllable parameters.

$$\frac{dF}{dt} = e^{(a_1+\sum_{j=2}^{8} a_j x_j)} \tag{2.1}$$

The normalization constants given in the general ROP equation are modified accordingly as a function of the data property when used as an input to the regression cycle. The coefficients should give accurate predictions for ROP; when modified normalization constants are used. The constants given in equation 2.2 from a_1 through a_8 should be determined through the multiple regression analysis using the drilling data. They represent the effects of formation strength, compaction effect, pressure differential, bit weight, rotary speed, tooth wear and hydraulic exponent.

The threshold bit weight on bit and bit diameter value is not constant, it significantly may have varying magnitudes based on formation characteristics, and for this reason whole data trend is observed when this threshold value is determiner as an input. The same value could easily be obtained from a drill-off test. The fractional tooth height calculation methodology is functions of reference abrasiveness constants in the same field, and is related to the time bit in use have operated. The general form ROP equation for roller cone bit types is given in equation 2.2.

$$\frac{dF}{dt} = Exp(a_1 + a_2(8000 - D) + a_3(D^{0.69}(g_p - 9) + a_4(g_p - P_c) + a_5 \ln\left(\frac{\frac{W}{d_b}-0.02}{4-0.02}\right) + a_6 \ln\left(\frac{N}{100}\right) + a_7(-h) + a_8(\frac{F_J}{1000}) \tag{2.2}$$

The considered effects of the controllable and uncontrollable drilling variables on ROP are individually described below for each item.

2.4.1 Formation Strength Function

The coefficient for the effect of formation strength is represented by a_1. It has been considered that the less the value for this constant, the less the penetration rate. The coefficient includes also the effects of parameters not mathematically modeled such as; the effect of drilled cuttings. Other factors which could be included for future consideration but known to be under this function could be drilling fluid details, solids content, efficiency of the rig equipment/material, crew experience, and service contractors' efficiency.

The equation for the formation strength related effects are defined as in equation 2.3. The f_1 term is defined in the same unit as rate of penetration, for that reason it is called drillability of the formation of interest.

$$f_1 = e^{a_1} \tag{2.3}$$

2.4.2 Formation Compaction Function

There are two function allocated for the consideration of the formation compaction over rate of penetration. The primary function for the effect of normal compaction trend is defined by a_2. The primary effect of formation compaction considers an exponential decrease in penetration rate with increasing depth, as given in equation 2.4. In other means this function assumes increasing rock strength with depth due normal compaction.

$$f_2 = e^{a_2 x_2} = e^{a_2(10000-D)} \tag{2.4}$$

The additional function considered to have an effect over the penetration rate in regards of the formation compaction is defined by the coefficient a_3. This function considers the effect of under compaction in abnormally pressured formation. In other means within over-pressured formations rate of penetration is going to show an increased behavior. There is an exponential increase in penetration rate with increasing pore pressure gradient, equation 2.5.

$$f_3 = e^{a_3 x_3} = e^{a_3 D^{0.69}(g_p - 9.0)} \quad (2.5)$$

2.4.3 Pressure Differential of Bottom Hole Function

The function for the pressure differential is defined by coefficient a_4. Pressure differential of hole bottom function is considered to reduce penetration rate with decreasing pressure difference. Whenever the pressure differential between the hole bottom and formation is zero the effect of this function is going to be equal to 1 for the overall process, equation 2.6.

$$f_4 = e^{a_4 x_4} = e^{2.303 a_4 D(g_p - \rho_c)} \quad (2.6)$$

2.4.4 Bit diameter and weight function

The function for the bit diameter and weight is defined by coefficient a_5. The bit weight and bit diameter are considered to have direct effect over penetration rate, equation 2.7. $(\frac{W}{d_b})$ is the threshold bit weight, the reported values for this term ranging from 0.6 to 2.0. In this the magnitude for this term has been determined specifically based on the characteristics of the formation. The force at which fracturing begins beneath the tooth is called the threshold force. The given function is normalized for 4000 lbf per bit diameter.

$$f_5 = e^{a_5 x_5} = \left(\frac{\frac{W}{d_b} - \left(\frac{W}{d_b}\right)_t}{4 - \left(\frac{W}{d_b}\right)_t} \right)^{a_5} \quad (2.7)$$

2.4.5 Rotary Speed Function

The function for the rotary speed is defined by coefficient a_6. Likewise the direct relation of bit weight on penetration rate the rotary speed is also set to have a similar relation, equation 2.8. The normalizing value to equalize the rotary speed function to 1 is taken to be an appropriate magnitude based on the actual rotation of the bit.

$$f_6 = e^{a_6 x_6} = \left(\frac{N}{100}\right)^{a_6} \tag{2.8}$$

2.4.6 Tooth Wear Function

The function for the tooth wear is defined by coefficient a_7. The tooth wear function is calculated by means of determining the fractional tooth height, the more the tooth wear the less the penetration rate, equation 2.9. In order to calculate the respective tooth height, a bit record for similar bit type that has been used within the same formation is necessary.

$$f_7 = e^{a_7 x_7} = e^{a_7(-h)} \tag{2.9}$$

2.4.7 Hydraulic Function

The function for the hydraulic effect is defined by coefficient a_8. The hydraulics function represents the effects of the bit hydraulics. Jet impact force was chosen as the hydraulic parameter of interest, with a normalized value of 1.0 for f_8 at 1,000 lbf, as given in equation 2.10.

$$f_8 = e^{a_8 x_8} = \left(\frac{F_j}{1000}\right)^{a_8} \tag{2.10}$$

CHAPTER 3

METHODOLOGY

3.1 Project Methodology

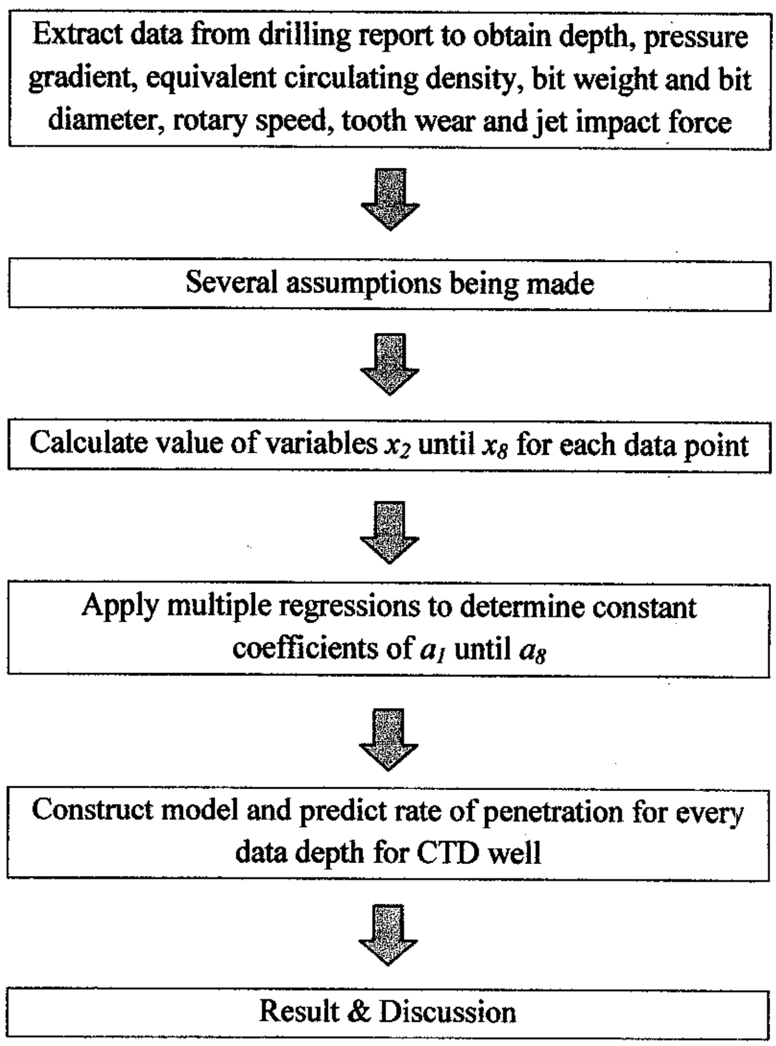

Figure 7: Project Methodology

3.2 Data Description

Drilling data available for this project was acquired from a field in a Malay basin.The formation is mainly formed in sequences alternating sandstone and shale layer. Table 1 gives the detailed description for the formation lithology.

Depth	Description	Fluid Type
5250-8920 ft	Sandstone, Shale	Water
8920-9560 ft	Sandstone, Shale	Gas and Oil
9560-11200 ft	Sandstone, Shale	Gas and Oil
11200-12000 ft	Sandstone, Shale	Gas and Oil
12000-13000 ft	Sandstone, Shale	Gas and Oil
13000ft above	-	Water

Table 1: LithologyDescription

The pore pressure and fracture gradient of the field is given in Table 2. Normal pressure is assumed which is 0.435 from surface to 9000ft. From 9000ft downward abnormal pressures are assume which increase in 100, 300, 600, 1000 and 1200 psi.

Depth	Pore Pressure (psi/ft)	Fracture Gradient (psi/ft)
0-9000 ft	0.435	0.595-0.682
9000-9600 ft	0.435D + 100	0.547-0.551
9600-11200 ft	0.435 D + 300	0.547-0.551
11200-12000 ft	0.435 D + 600	0.576-0.709
12000-13000 ft	0.435 D + 1000	0.576-0.709
13000ft above	0.435D + 1200	0.576-0.709

Table 2: Pore Pressure and Fracture Gradient

Table 3 gives the casing and formation top details of the field used in this project. The total depth of the well is 13000ft. The conductor pipe of the wells has been installed to a depth of about 100m.

Depth (fttvdss)	Casing Size (in)	Grade Coupling	Weight (lb/ft)
0-325	30	ATD SQUNCH	310
325-2000	20	K55 BTC	133
2000-5900	13 3/8	N80 BTC	0-100 (72)
			100-4700 (68)
			4700-5900 (72)
5900-10800	9 5/8	P110 BTC	47
10800-13000	7	N80 VAM	29

Table 3: Casing Program

Table 4 gives the bit and hydraulic program for the wells. The details include bit size, bit type, nozzle sizes, pump rate, mud gradient, weight on bit and rotary speed.

Depth (tvdss)	Bit Size (Inch)	Bit Type (IADC Code)	Nozzle Size (1/32 inch)	Pump Rate (GPM)	Mud Gradient (Psi/1000)	Weight On Bit (Lbs × 1000)	RPM
325-2000	12 1/4	114	3×18	700-750	460	25-35	100-120
	26	111	3x28	950-1100		30-45	
2000-5900	12 1/4	114 PDC(PD4/BX7LM)	3×16	750-800	470	30-35	100-120 140(PDC)
	17 1/2	114/135	3×18	800-900	470	35-40	100-120
5900-10800	12 1/4	114 PDC(PD4/BX7LM PD5/TD290)	3×16	750-800	500	35-40 15-25	100-120 140-120
10800-13000	8 1/2	114 PDC(PD4/TD290/PD5BX7LM)	3×14	400-450 400-500	550 550	15-20 15-20	100-120 120-140

Table 4: Bit and Hydraulic Program

Table 5 provides the design mud program which includes type of mud, mud weight, plastic viscosity and yield point.

Depth (fttvdss)	Type	Grad (pptf)	Plastic Viscosity	Yield Point
325-2000	SLS	460	10 to 12	8 to 10
2000-5900	SLS	470	12 to 15	10 to 12
5900-10800	EA-IOEM	500	20 to 25	15 to 18
10800-13000	EA-IOEM	550	30 to 35	15 to 20

Table 5: Mud Program

3.3 Data process - Multiple Regression Analysis

Figure 8 gives the multiple regression process cycle. The first step in the process is to have the x_2 until x_8 variables calculated for each data point. The next step is to accordingly collate the calculated the variables in order to create the matrix. In the scope of this study a matrix of 8×8 is being created. Once the matrix has been calculated the same can be solved and the constant a_1 until a_8 that represent the field could be determined.

Calculation of x_2 until x_8 for each data point

↓

Data capture for x_2 until x_8

↓

Creation of matrix for each a_1 until a_8

↓

Determination of a_1 until a_8

Figure 8: Multiple Regression Process Cycle

The calculation of x_2 until x_8 is using the equation of 3.1 until 3.7. This calculation is tabulated in the excel spreadsheet to make it easier for multiple regression analysis later.

$$x_2 = 10000 - D \tag{3.1}$$

$$x_3 = D^{0.69}(g_p - 9.0) \tag{3.2}$$

$$x_4 = D\,(g_p - \rho_c) \tag{3.3}$$

$$x_5 = \ln\left(\frac{\frac{W}{d}}{4.0}\right) \tag{3.4}$$

$$x_6 = \ln\left(\frac{N}{100}\right) \tag{3.5}$$

$$x_7 = -h \tag{3.6}$$

$$x_8 = \ln\left(\frac{F_j}{1000}\right) \tag{3.7}$$

Once x_2 until x_8 have been calculated, multiple regressions are performed. Microsoft Excel has been used to process the data that available. Appendix A gives the example of written code for the multiple regression process. This way the program has been utilized to solve the constant a_1 until a_8 of the accurately.

When the constant a_1 until a_8 have been required, the ROP for each data point can be calculated.

3.4 Assumptions Made

Bourgouyne and Young model is a model constructed for the conventional rotary drilling system. Not just the model, others model too. There is no model being formed specifically for CTD operations.

But the model still can be used to predict the rate of penetration for CTD well by having several assumptions made to poin out the differences CTD operations with the conventional rotary drilling system. Differences of CTD with the conventional well for the Bourgoyne and Young ROP calculation are;

1. Higher rotary speed.
2. Lower weight on bit.
3. 0 value for bit wear because use PDC bit for whole operation.

CHAPTER 4

RESULT AND DISCUSSIONS

Table 6 shows the important parameters which include depth, drilling rate, bit weight, rotary speed, tooth wear, jet impact force, pore pressure gradient and equivalent circulating density that had been extracted from drilling report.

4.1 Field Data

Data Entry	Depth(ft)	Bit No.	PoreGradient(lb/gal)	Bit Weight (1,000 lb/in.)	Rotary Speed(rpm)	Tooth Wear	JetImpactForce	ECD(lb/gal)	Drilling Rate (ft/hr)
1	2150	2	8.365	0.82	120	0	0.882	8.93	171
2	2155	7	8.365	0.57	140	0	0.819	9.06	20
3	3591	8	8.365	0.74	160	0	1.29	9.11	160
4	5190	10	8.365	1.63	130	0	1.29	9.11	82
5	5872	11	8.365	0.95	140	0	1.29	9.11	49
6	6000	12	8.365	0.33	180	0	1.29	9.11	43
7	6080	16	8.365	1.63	140	0	1.062	9.49	64
8	6322	17	8.365	1.34	140	0	0.772	9.67	36
9	6592	18	8.365	1.8	160	0	0.772	9.67	27
10	6679	19	8.365	0.57	150	0	1.338	9.69	14
11	7341	20	8.365	1.63	180	0	1.145	9.69	83
12	8921	21	8.365	1.63	180	0	1.216	9.68	46
13	9363	22	8.571	1.63	180	0	0.868	9.88	47
14	9652	23	8.96	1.13	170	0	1.192	9.96	19
15	9660	24	8.96	1.31	160	0	1.192	9.96	3
16	10662	25	8.91	1.13	160	0	1.097	9.96	34
17	10735	26	8.9	1.43	150	0	1.192	9.96	16
18	10900	27	8.89	0.82	180	0	1.034	9.96	35
19	11214	28	8.88	0.99	120	0	1.114	9.96	12
20	11224	31	9.39	1.65	140	0	0.903	11.1	5
21	11481	32	9.37	1.76	170	0	0.975	11.02	26
22	12885	33	9.86	1.76	160	0	0.975	11.02	28
23	13180	34	10.12	1.76	180	0	0.825	10.96	11
24	13810	35	10.04	1.76	150	0	0.632	10.97	21
25	14300	37	9.98	1.76	160	0	0.632	10.95	15

Table 6: Field Data

4.2 Calculation of Variable x_2 until x_8

A spreadsheet was created to determine the value of x_2 until x_8 which represent variables of under compaction, normal compaction, pressure differential, weight on bit, rotary speed, bit tooth wear and jet impact force. These are based on equations 3.1 until 3.7. These values are needed before applying multiple regression analysis to get the constants coefficients of a_1 until a_8 for the field. Table 7 shows the calculated value for the field.

x_2	x_3	x_4	x_5	x_6	x_7	x_8	Y
7850	-127	-1215	-1.585	0.182	0	-0.126	5.142
7845	-127	-1498	-1.948	0.336	0	-0.200	2.996
6409	-180	-2675	-1.687	0.470	0	0.255	5.075
4810	-232	-3867	-0.898	0.262	0	0.255	4.407
4128	-253	-4375	-1.438	0.336	0	0.255	3.892
4052	-255	-4431	-2.495	0.588	0	0.255	3.761
3920	-259	-6840	-0.898	0.336	0	0.060	4.159
3678	-266	-8250	-1.094	0.336	0	-0.259	3.584
3408	-274	-8603	-0.799	0.470	0	-0.259	3.296
3321	-277	-8850	-1.948	0.405	0	0.291	2.639
2659	-295	-9727	-0.898	0.588	0	0.135	4.419
1079	-338	-11731	-0.898	0.588	0	0.196	3.829
637	-236	-12256	-0.898	0.588	0	-0.142	3.850
348	-22	-9652	-1.264	0.531	0	0.176	2.944
340	-22	-9660	-1.116	0.470	0	0.176	1.099
-662	-54	-11195	-1.264	0.470	0	0.093	3.526
-735	-60	-11379	-1.029	0.405	0	0.176	2.773
-900	-67	-11663	-1.585	0.588	0	0.033	3.555
-1214	-75	-12111	-1.396	0.182	0	0.108	2.485
-1224	243	-19193	-0.886	0.336	0	-0.102	1.609
-1481	234	-18944	-0.821	0.531	0	-0.025	3.258
-2885	589	-14947	-0.821	0.470	0	-0.025	3.332
-3180	780	-11071	-0.821	0.588	0	-0.192	2.398
-3810	748	-12843	-0.821	0.405	0	-0.459	3.045
-4300	722	-13871	-0.821	0.470	0	-0.459	2.708

Table 7: Calculation for $x_2 - x_8$

4.3 Multiple Regression Analysis

After obtaining the value of x_2 until x_8, multiple regression analysis was performed to obtain constant coefficients of a_1 until a_8 for the field. Table 8 shows the results of the analysis.

Variable	Constant	Value
Drillability	a_1	4.948
Normal Compaction	a_2	1.60E-04
Under Compaction	a_3	6.02E-05
Pressure Differential	a_4	6.61E-05
Weight On Bit	a_5	1.306
Rotary Speed	a_6	0.704
Tooth Wear	a_7	0
Jet Impact Force	a_8	0.206

Table 8: Determination of constant a_1-a_8 for field

Based on the values of constant coefficients, the model for the field based on Bourgoyne and Young ROP model can be constructed as below:

$$f(x) = Exp(3.91 + 9.45(800 - D) + 6.86 \times 10 - 5\left(D^{0.69}(g_p - 9)\right) + 8.64 \times 10 - 5D(g_p - P_c) + 0.37\ln\left(\frac{\frac{W}{d_b} - 0.02}{4 - 0.02}\right) + 2.23\ln\left(\frac{N}{100}\right) + 0.0025(-h) + 0.67\left(\frac{F_J}{1000}\right) \quad \textbf{(4.1)}$$

4.4 Rate of Penetration Calculation

Rate of penetration for every data depth was calculated using the model that had been constructed in Equation 4.1. Table 9 shows the calculated rate of penetration that was obtained.

a_1	a_2x_2	a_3x_3	a_4x_4	a_5x_5	a_6x_6	a_7x_7	a_8x_8	Sum	CTD ROP (ft/hr) = exp (Sum)
4.948	1.257	-0.0076	-0.080	-2.070	0.1284	0	-0.0259	4.150	63.4
4.948	1.256	-0.0076	-0.099	-2.545	0.2370	0	-0.0412	3.748	42.5
4.948	1.026	-0.0109	-0.177	-2.204	0.3311	0	0.0525	3.966	52.8
4.948	0.770	-0.0140	-0.256	-1.173	0.1848	0	0.0525	4.513	91.2
4.948	0.661	-0.0153	-0.289	-1.651	0.3311	0	0.0525	4.037	56.7
4.948	0.649	-0.0154	-0.293	-1.892	0.4141	0	0.0525	3.864	47.6
4.948	0.627	-0.0156	-0.452	-1.173	0.2370	0	0.0124	4.185	65.7
4.948	0.589	-0.0161	-0.546	-1.428	0.2370	0	-0.0534	3.731	41.7
4.948	0.546	-0.0165	-0.569	-1.087	0.3311	0	-0.0534	4.099	60.3
4.948	0.532	-0.0167	-0.585	-2.545	0.2856	0	0.0601	2.679	14.6
4.948	0.426	-0.0178	-0.643	-1.080	0.4141	0	0.0279	4.075	58.9
4.948	0.173	-0.0204	-0.776	-1.173	0.4141	0	0.0404	3.607	36.8
4.948	0.102	-0.0142	-0.811	-1.173	0.4141	0	-0.0292	3.438	31.1
4.948	0.056	-0.0014	-0.638	-1.651	0.3738	0	0.0362	3.123	22.7
4.948	0.054	-0.0014	-0.639	-1.458	0.3311	0	0.0362	3.272	26.4
4.948	-0.106	-0.0033	-0.741	-1.390	0.4141	0	0.0191	3.142	23.1
4.948	-0.118	-0.0036	-0.753	-1.344	0.2856	0	0.0362	3.053	21.2
4.948	-0.144	-0.0041	-0.771	-0.932	0.4141	0	0.0069	3.518	33.7
4.948	-0.194	-0.0045	-0.801	-1.448	0.2856	0	0.0223	2.808	16.6
4.948	-0.196	0.0147	-1.270	-1.157	0.2370	0	-0.0211	2.557	12.9
4.948	-0.237	0.0141	-1.253	-0.979	0.4141	0	-0.0052	2.902	18.2
4.948	-0.462	0.0355	-0.989	-1.072	0.4141	0	-0.0052	2.870	17.6
4.948	-0.509	0.0470	-0.732	-1.072	0.4141	0	-0.0397	3.056	21.2
4.948	-0.610	0.0451	-0.850	-0.986	0.4141	0	-0.0947	2.867	17.6
4.948	-0.688	0.0435	-0.918	-0.918	0.3738	0	-0.0947	2.747	15.6

Table 9: ROP Calculation

4.5 CTD and Actual ROP

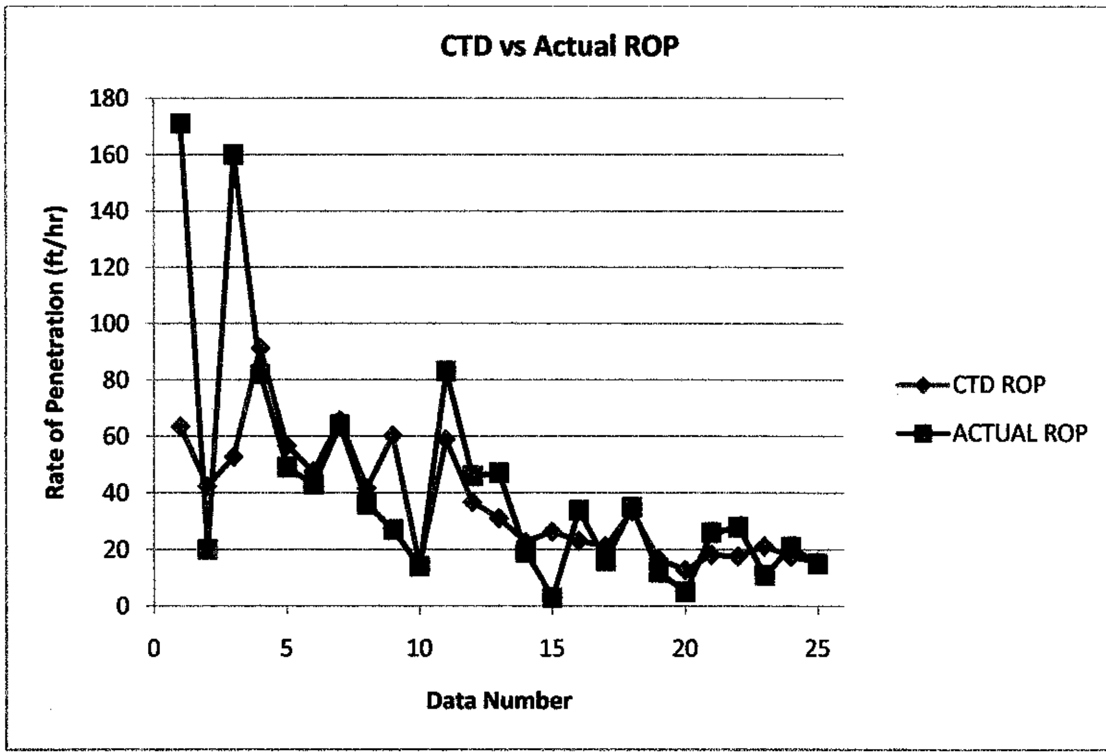

Figure 9:CTD vs. Actual ROP

Figure 9 shows the graph of actual rate of penetration that had been taken from the actual field compared to the predicted rate of penetration for CTD using the Bourgoyne and Young rate of penetration model. There are 10 data points which are lower compare to the actual field ROP value. The total data points are 25. The overall value CTD ROP is not that far away from the actual field value. So the potential of CTD to be applied in Malay is big and the point where the CTD ROP is lower can be optimized to get the better result. By optimize the factors such as weight on bit, rotary speed and other; we can manipulate the advantage of CTD to the greater extent.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

Bourgoyne and Young had been selected in this study to determine the rate of penetration value for CTD and also conventional drilled well. There are other mathematical model to determine the rate of penetration value for both cases but the Bourgoyne and Young being selected.

It is because the Bourgoyne and Young model is based on statistical synthesis of the past drilling parameters. A linear penetration model is being introduced and multiple regression analysis over introduced rate of penetration equation is being conducted. For that reason this method is considered to be the most suitable method to determine the rate of penetration value.

The model also regarded as the most complete mathematical to calculate rate of penetration. It takes into consideration many factor influences the drilling operation likes the pressure gradient, drill bit specification, formation compaction and others.

Only 10 out of 25 point of data, CTD's well rate of penetration value is recordedlower thanthe actual field rate of penetration. It is consistent with the founding of higher rate of penetration recorded when using coiled tubing drilling compare when using the conventional rotary drilling system.These values can be higher by optimizing factors of CTD operations such as weight on bit, rotary speed, and other to manipulate the advantage of CTD with respect to the point of depth for the field.

The rate of penetration recorded in this study can be a compliment to the cost reduction and technical simplicity offered by CTD for re-entry horizontal well using CTD as redevelopment strategy for mature field in the Malay Basin.

5.3 Recommendations

The model constructed in this project can be developed further with more reliable and updated data from the field. This can help to suit the drilling operations with the latest field conditions.

In future work, several parameters that was not include in the model but relate to rate of penetration should be included such as drilling fluid details, solids content and efficiency of the rig equipment/material. These will make sure the model is reliable thus the optimization is more accurate.

The used of multiple regression analysis for prediction of coefficient could be replaced by more sophisticated and modern statistical method. Recent studies include several statistical methods that can be applied to obtain more accurate coefficient such as Genetic Algorithm (G.A) or Artificial Neural Network.

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APPENDICES

Appendix A: Example of Multiple Regression Analysis Code

```
Model = "= "
Model = Model & """Y"""
Model = Model &" & "
Model = Model & """ = """
'The information for the model statement is taken from the _
worksheet and not hard coded.
For i = 1 To p
If Intercept = i Then
temp = " & " & "round(B19,2)"
Else
temp = " &if(sign(B" & 18 + i & ")=-1, "" "","" + "")" & _
" & " & "Round(B" & 18 + i & ", 2)" & " & " & _
""" """ &" & " & "A" & 18 + i
End If
Model = Model & temp
Next i
Call Progress(0.75) 'update procedure's progress
'*********************************************************************************
'****************************** OUTPUT ****************************************
'*********************************************************************************
'Output in new worksheet
'Check workbook for a worksheet named "Regression"
For Each wksInApplication.Worksheets
If wks.name = "Regression" Then wks.Delete
Next
'Place new worksheet after the last worksheet in the workbook
cntsheets = Application.Sheets.Count
Set newsheet = Application.Worksheets.add(after:=Worksheets(cntsheets))
newsheet.name = "Regression"
FinalCol = 0
Call Progress(0.8) 'update procedure's progress
'Get the sheet name-either new or existing
ShtName = Application.ActiveSheet.name
With Application
'Place the data in the worksheet along with variable names
.Cells(1, 13 + p).Value = Varnames(1)
.Range(Cells(2, 13 + p), Cells(n + 1, 13 + p)).Value = y
For i = 1 To p
If Intercept = i Then
```

```
.Cells(1, 13 + p + i).Value = "Intercept"
Else
.Cells(1, 13 + p + i).Value = Varnames(i + 1 - Intercept)
End If
Next i
.Range(Cells(2, 14 + p), Cells(n + 1, 13 + p + p)) = Data
'Insert the range formula for the X'Xinv
.Cells(1, 8).Value = "X'X inverse"
.Range(Cells(2, 8), Cells(1 + p, 7 + p)).FormulaArray = _
"=MINVERSE(MMULT(TRANSPOSE(RC[" & 6 + p & _
"]:R[" & n - 1 & "]C[" & 5 + p + p & "]),RC[" & 6 + p & _
"]:R[" & n - 1 & "]C[" & 5 + p + p & "]))"
'Insert the fomulae for the variance-covariance matrix
.Cells(2 + p, 8).Value = "Variance-covariance matrix"
.Range(Cells(3 + p, 8), Cells(p * 2 + 2, 7 + p)).FormulaR1C1 = _
"=R8C4*R[-" & 1 + p & "]C"
'Build the correlation matrix using the 'Correl' function
'Must apply the function to all combinations to get lower _
triangular of correlation matrix--get other half by symmetry
.Cells(3 + 2 * p, 8).Value = "Correlation matrix"
For i = 1 To p - Intercept
.Cells(3 + 2 * p + i, 7 + i).Value = 1#
For j = i + 1 To p - Intercept
.Cells(3 + 2 * p + j, 7 + i).FormulaR1C1 = _
"=Correl(R2C" & 13 + p + Intercept + i & _
":R" & n + 1 & "C" & 13 + p + Intercept + i & "," & _
"R2C" & 13 + p + Intercept + j & ":R" & n + 1 & "C" & _
13 + p + Intercept + j & ")"
.Cells(3 + 2 * p + i, 7 + j).FormulaR1C1 = _
"=R[" & j - i & "]C[-" & j - i & "]"
Next j
Next i
'Calculate the inverse of the correlation matrix
Cells(4 + 2 * p + p - Intercept, 8).Value = "Inverse Correlation Matrix"
.Range(Cells(5 + 2 * p + p - Intercept, 8), _
Cells(4 + 2 * p + 2 * (p - Intercept), 7 + p - Intercept)).FormulaArray = _
"=MINVERSE(R" & 4 + 2 * p & "C8:R" & 3 + 2 * p + p - Intercept & _
"C" & 7 + p - Intercept & ")"
Call Progress(0.85) 'update procedure's progress
'Output ANOVA table
.Cells(1, 1).Value = "Regression Analysis of " &Varnames(1)
.Cells(1, 1).Font.Bold = True
.Cells(3, 1).Value = "Regression equation:"
On Error Resume Next
.Cells(3, 2).Value = Model
On Error GoTo 0
.Cells(5, 2).Value = "Sum of"
.Cells(5, 3).Value = "Degrees of"
```

```
.Cells(5, 4).Value = "Mean"
.Cells(6, 1).Value = "Source of Variation"
.Cells(6, 2).Value = "Squares"
.Cells(6, 3).Value = "Freedom"
.Cells(6, 4).Value = "Square"
.Cells(6, 5).Value = "F"
.Cells(6, 6).Value = "P-value"
'Output fitted values.Cells(1, 9 + p).Value = "Fits"
.Range(Cells(2, 9 + p), Cells(n + 1, 9 + p)).FormulaR1C1 = _
"=MMULT(RC[5]:RC[" & 4 + p & "],R19C2:R" & 18 + p & "C2)"
'Output residuals
.Cells(1, 10 + p).Value = "Resids"
.Range(Cells(2, 10 + p), Cells(n + 1, 10 + p)).FormulaR1C1 = _
"=RC[3]-RC[-1]"
'Output regression sum of squares
.Cells(7, 1).Value = "Regression"
.Cells(7, 2).FormulaR1C1 = "=R[2]C-R[1]C"
.Cells(7, 3).Value = p - Intercept
.Cells(7, 4).FormulaR1C1 = "=RC[-2]/RC[-1]"
.Cells(7, 5).FormulaR1C1 = "=RC[-1]/R[1]C[-1]"
'Output error sum of squares
.Cells(8, 1).Value = "Error"
.Cells(8, 2).FormulaR1C1 = _
"=SUMSQ(R2C" & 10 + p & ":R" & n + 1 & "C" & 10 + p & ")"
.Cells(8, 3).Value = n - p
.Cells(8, 4).FormulaR1C1 = "=RC[-2]/RC[-1]"
'Output total sum of squares
.Cells(9, 1).Value = "Total"
If Intercept = 1 Then
.Cells(9, 2).FormulaR1C1 = _
"=DEVSQ(R2C" & 13 + p & ":R" & n + 1 & "C" & 13 + p & ")"
Else
.Cells(9, 2).FormulaR1C1 = _
"=SUMSQ(R2C" & 13 + p & ":R" & n + 1 & "C" & 13 + p & ")"
End If
'Output error degrees of freedom
.Cells(9, 3).Value = n - Intercept
'Output RMSE
.Cells(11, 2).Value = "s"
.Cells(11, 3).FormulaR1C1 = "=SQRT(R[-3]C[1])"
.Cells(11, 3).NumberFormat = "0.0000"
'Output Rsq only with intercept model
If Intercept = 1 Then
.Cells(12, 2).Value = "R-sq"
.Cells(12, 3).FormulaR1C1 = "=R[-5]C[-1]/R[-3]C[-1]"
.Cells(12, 3).NumberFormat = "0.00%"
.Cells(13, 2).Value = "R-Sq(adj)"
.Cells(13, 3).FormulaR1C1 = "=1-R8C4/(R9C2/R8C3)"
```

```
.Cells(13, 3).NumberFormat = "0.00%"
End If
'Output table of coefficient estimates, etc.
.Cells(16, 1).Value = "Parameter Estimates"
.Cells(18, 1).Value = "Predictor"
.Cells(18, 2).Value = "CoefEst"
.Cells(18, 3).Value = "Std Error"
.Cells(18, 4).Value = "t value"
.Cells(18, 5).Value = "P-value"
'General formatting
'Draw lines on ANOVA table
Range(.Cells(4, 1), Cells(4, 6)) _
.Borders(xlEdgeBottom).LineStyle = xlContinuous
Range(.Cells(6, 1), Cells(6, 6)) _
.Borders(xlEdgeBottom).LineStyle = xlContinuous
Range(.Cells(9, 1), Cells(9, 6)) _
.Borders(xlEdgeBottom).LineStyle = xlContinuous
'Draw line for table of coefs, se, VIFs, t & p statistics
Range(.Cells(18, 1), Cells(18, 5)) _
.Borders(xlEdgeBottom).LineStyle = xlContinuous
.Columns(1).ColumnWidth = 18
.Columns(3).ColumnWidth = 11
.Columns(4).ColumnWidth = 9.75
.Range(Cells(7, 5), Cells(7, 6)).NumberFormat = "0.0000"
'Output the coefficient estimates
.Range(Cells(19, 2), Cells(18 + p, 2)).FormulaArray = _
"=MMULT(R2C8:R" & 1 + p & "C" & 7 + p & _
",MMULT(TRANSPOSE(R2C" & 14 + p & ":R" & _
n + 1 & "C" & 13 + 2 * p & ")," & _
"R2C" & 13 + p & ":R" & n + 1 & "C" & 13 + p & "))"
'OuputSEs, t values, pvalues, and VIFs
For i = 1 To p
'Output variable names
If i = 1 Then
If Intercept = 1 Then
.Cells(i + 18, 1).Value = "Constant"
Else
.Cells(i + 18, 1).Value = Varnames(i + 1)
End If
Else
.Cells(i + 18, 1).Value = Varnames(i)
End If
.Cells(i + 18, 2).NumberFormat = "0.0000"
'Output standard errors
.Cells(i + 18, 3).FormulaR1C1 = _
"=SQRT(R" & 2 + p + i & "C[" & 4 + i & "])"
.Cells(i + 18, 3).NumberFormat = "0.0000"
.Cells(i + 18, 4).NumberFormat = "0.0000"
```

```
.Cells(i + 18, 5).NumberFormat = "0.0000"
'Output VIFs
If i > 1 And Intercept = 1 And p > 2 Then
.Cells(18, 6) = "VIFs"
.Cells(i + 18, 6).FormulaR1C1 = _
"=R" & 3 + 3 * p - Intercept + i & "C[" & i & "]"
.Cells(i + 18, 6).NumberFormat = "0.0000"
.Cells(18, 6).Borders(xlEdgeBottom) _
.LineStyle = xlContinuous
End If
Next i
Call Progress(0.9) 'update procedure's progress
'Write note detailing the use of observations
If IsEmpty(Missing) Then
.Cells(i + 19, 1) = n & _
" observations were used in the analysis."
Else
.Cells(i + 19, 1) = n & _
" observations were used in the analysis."
'Two statements to get the verb tense correct
If UBound(Missing, 1) = 1 Then
.Cells(i + 20, 1) = UBound(Missing, 1) & _
" observation was excluded due to missing values."
Else
.Cells(i + 20, 1) = UBound(Missing, 1) & _
" observations were excluded due to missing values."
End If
End If
'****************************
' Diagnostic Calculations
'****************************
'Output the value of the determinant of the correlation matrix
.Cells(11, 4) = "Determinant"
.Range(Cells(11, 5), Cells(11, 5)).FormulaArray = _
"=MDETERM(R" & 4 + 2 * p & _
"C8:R" & 3 + 2 * p + p - Intercept & _
"C" & 7 + p - Intercept & ")"
Call Progress(0.95) 'update procedure's progress
'Durbin-Watson statistic
.Cells(1, 11 + p).Value = "Durbin-Watson"
.Range(Cells(3, 11 + p), Cells(n + 1, 11 + p)).FormulaR1C1 = _
"=(RC[-1]-R[-1]C[-1])^2"
.Cells(12, 4) = "DW"
.Cells(12, 5).FormulaR1C1 = _
"=SUM(R3C" & 11 + p & ":R" & n + 1 & "C" & 11 + p & ")/R8C2"
.Cells(12, 5).NumberFormat = "0.00"
'Output processing time
.Worksheets(ShtName).Cells(22 + p, 1) = _
```

```
"Computational time: "& .Round(Timer - Time, 2) & " seconds."
Call Progress(1) 'update procedure's progress
'resume worksheet calculations
.Calculation = xlCalculationAutomatic
'Calculate probabilities after worksheet calculations _
have been set to automatic
't values
.Range(Cells(19, 4), Cells(18 + p, 4)). _
FormulaR1C1 = "=RC[-2]/RC[-1]"
'p values
.Range(Cells(19, 5), Cells(18 + p, 5)). _
FormulaR1C1 = "=(1-TCDF(abs(RC[-1]),R8C3))*2"
'F value
.Cells(7, 6).FormulaR1C1 = "=1-FCDF(RC[-1],RC[-3],R[1]C[-3])"
End With
Unload Me
End
EndProc:
Application.Calculation = xlCalculationAutomatic 'resume worksheet calculations
MsgBox ("Procedure has encountered a fatal error and will terminate. "& _
"Error code: "& Err)
Unload Me
End Sub
Sub Progress(Pct)
'This sub updates the width of the bar moving across the _
progress indicator frame and the % complete caption
With Me
.Progress_Frame.Caption = FormatPercent(Pct, 0)
.ProgressBar.Width = Pct * .Progress_Frame.Width
.Repaint
End With
End Sub
```