ESP MOTOR RATINGS

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An electric motor is similar in some respects to a resistor in that its power rating is a function of the maximum operating temperature of the materials. In electrical apparatus, as far as temperature is concerned, it is permissible to overload the device as long as the safe operating temperature is not exceeded (Ref 1). The temperature of the device is a function of the temperature of its environment and its ability to transfer heat to its surroundings. To be accurate, the horsepower rating of an ESP motor should take this into account. This paper reviews the major factors controlling the generation and the dissipation of energy in a ESP motor and presents a work sheet for approximating the maximum well temperature an ESP motor for acceptable run life.

RE-RATING MOTORS

Each manufacturer follows their own philosophy in attempting to deliver to their customers the best value. When the price of oil dropped and the money became tight the manufactures re-examined the "one size fits all" philosophy. Obviously a motor designed for a 250 degree well was over designed for a 110 degree well. Re-rating the motors to take into account the conditions under which they will operate provides a better over all economy for the industry. This concept, although simple to accept for an industry as a whole, is more difficult to explain on an individual basis. It is hard to convince a customer that he is getting a better value when the new 100 horsepower motor that he purchased is three feet shorter than the old one that he sent in for repair.

The main determinator of value in a motor is run life. If you can obtain the same motor run life, the length of the motor is not relevant.

The key elements controlling motor run life are the dielectric strength and the mechanical durability of the electrical insulation. Both of these deteriorate with time and temperature.

The rule of thumb for this time temperature relation for insulation states that the time to failure is halved for each 10 degrees C (18 degrees F) increase in the internal operating temperature. (Ref 2) Insulations are rated on the basis of their ability to maintain dielectric resistance and mechanical integrity under continued exposure to a specific temperature.

A simplified thermal model, Figure 1, is used to develop relations to estimate the internal temperature of the ESP motor. Electrical energy flows into the motor where it is converted into mechanical energy (shaft horsepower). The quantity of heat energy that must be dissipated to the surroundings is a function of the efficiency of this conversion (motor efficiency). The temperature difference between the motor and its surroundings is the driving force for the flow of the heat energy. The heat transfer mechanism and physical properties of the surroundings effect the resistance to this heat flow.

The model uses a set of simplified equations to develop multipliers. These multipliers represent the change in heat generation and heat transfer as conditions deviate from the assumed nominal. These changes are used to estimate the maximum limit for the well temperature in order for the motor to maintain the designed margins of safety.

TEMPERATURE LIMIT OF A MOTOR

Because of the hostile conditions, the ESP manufactures use the best insulation available. The highest rating for insulation is class "H", rated for 180 degrees C (356 degrees F) (Ref 1). This is the temperature that, above which, you would start seeing a decrease in the insulation life. The material generally used for ESP motors had a maximum temperature rating higher than class "H", but NEMA has no category above this.

To construct the model we need to establish the internal temperature rise of the motor at ideal conditions, make estimates of how deviations from the idea effect the heat generated and the heat transferred.

INTERNAL OPERATING TEMPERATURE

The actual temperature experienced by the insulation in an ESP motor is composed of two elements; 1) the temperature of the environment (well temperature) and 2) the temperature rise necessary to transfer the residual heat to the environment. The residual heat is the thermal energy in the system resulting from the inefficiency in converting electrical energy to mechanical energy. In an ESP, cooling occurs through heat transfer to the production fluid as it moves over the motor O.D.

Operating Temperature = Ambient Temp. + Temp Rise

Example:

A motor requires a temperature rise of 40 degrees to transfer the residual heat to the surroundings.

If the well temperature is 250 degrees;
Motor internal temperature = 40 + 250 = 290 degrees

If the well temperature was 150 degrees;
Motor internal temperature = 40 + 150 = 190 degrees

It is standard practice for motor suppliers to rate their motors for a maximum well temperature. In this industry, 250 degree F is common, but there are motors rated for 200 and 300 degrees F.

Given the 356 degree F constraint for class "H" insulation, we can develop a "Temperature Rise Allowance" for an ESP motor by subtracting the temperature rating from 356 degrees.

Temperature Rise Allowance (TRA) = 356 - Rated Temperature

This allowed temperature rise is comprised of the rise anticipated under ideal conditions plus a factor of safety. It would be expected that the run life of the motor would be reduced it this allowance was exceeded. A motor rated for 250 degrees F, has a TRa of 106 degrees F. If a safety factor of 2 was selected for the motor, the actual temperature rise under ideal conditions or Design Temperature Rise (TRd) would be 53 degrees F.

Design Temperature Rise(TRd) = TRa/SF

MOTOR HEATING

There are two variables that significantly affect the heat generated in a motor; 1) the load on a motor and its resulting efficiency, and 2) non-design voltage of the motor and the balance of the power.

Motor Load and Efficiency

Figure 2 represents a typical motor performance curve. The operating characteristics are presented as a function of motor load. These curves are available from the manufacturer.

At rated load, the motor efficiency is at or near its maximum. As the load is moved from this point, the efficiency changes. Efficiency is defined as the ratio of the power output (name plate horsepower) to the required power input.

$$\text{Efficiency} = \text{Power Out}/\text{Power In}$$

The rate at which heat is generated is the difference between the input power and the output. It can be calculated using the efficiency from the motor curve and the output horsepower.

$$\text{Heat Generation Rate} = (746 \times Hp)/Eff - (746 \times Hp) \text{ Watts}$$

or:

$$\text{Heat Generation Rate} = 746 \times Hp\ (1/Eff - 1) \text{ Watts}$$

To develop a Operating Load Multiplier (Mol) to represent change in the internal heating of a motor under non ideal conditions, the new rate of heat generation is divided by the rate for the ideal conditions.

$$\text{Operating Load Multiplier(OLM)} = \frac{Hp(Opp)}{Hp(Rated)} \times \frac{(1/Eff(Opp)-1)}{(1/Eff(Rated)-1)}$$

Non Design Voltage and Power Balance

There are two significant conditions relative to motor voltage that effect motor temperature rise; nom-design voltage and unbalanced power.

Figure 3 shows the effects of voltage on a motor being operated at a fixed horsepower load. As voltage increases, the flux density in the motor laminations increases. This results in improved efficiency and lower heat generation, until the point is reached at which the laminations become saturated.

Though motor performance relative to voltage supplied it is also specific to the design, this type of curve should be available from all ESP motor suppliers. This curve shows that temperature rise will decrease to 93% of nominal with an increase in voltage up to about 110% of nominal value. After this the temperature will increase due to over saturation. This temperature increase will be used directly in our calculations as the Motor Voltage Multiplier (Mmv).

Unbalanced Voltage

When the line voltages applied to a three phase motor are not equal, unbalanced currents in the stator windings will result. The currents will be unbalanced in the order of 6 to 10 times the voltage imbalance. (Ref 2). The effect of these unbalanced currents is to introduce a negative sequence current, or a counter rotating magnetic field moving at twice the RPM as the synchronous magnet field. It requires extra energy from the motor to overcome these negative sequence fields which is results in more heat.

The percent of voltage imbalance is defined according to NEMA as:

$$\% \text{ Imbalance} = 100 \times \frac{\text{Maximum Deviation from Average}}{\text{Average Voltage}}$$

Although precise calculation of the impact of voltage imbalance on efficiency and motor temperature rise depends heavily on specific motor design, a good rule of thumb is that the temperature rise is twice the square of the voltage imbalance. A Voltage Imbalance Multiplier Multiplier (Mvi) is calculated as follows:

Voltage Imbalance Multiplier (Mvi) = 1 + 2 x (% Imbalance)^2/100

MOTOR COOLING

Two variables which significantly effect motor cooling will be considered; 1) Velocity of the fluid past the motor and 2) Specific heat of the fluid.

Fluid Velocity

Figure 4. shows the relationship between motor temperature rise and flow past the motor. Due to the physics of forced convection cooling, when fluid velocity falls below 1 ft/sec, temperature changes significantly with small changes in velocity. Above above 1 ft/sec, increased velocity has little or no effect on the temperature rise. The temperature rise at velocities less that .2 ft/sec is so dramatic that operation in this area is not recommended.(Ref 4)

Velocity past the motor can be calculated from the formula:

$$\text{Fluid Velocity (fps)} = \frac{0.012 * Q\ (BPD)}{(\text{Casing ID}^2 - \text{Motor OD}^2)}$$

The flow rate should ideally be heald at or above 1 ft/sec. (Ref 4) To achieve this rate, motor shrouds are often used. These shrouds act as artificially smaller casing, and force the fluid to flow over the motor at an increased velocity. Problems begin to arise when the motor can not be shrouded and the velocity is below 1 ft/sec.

A conservative estimate of the impact of reduced flow at rates between .2 and 1 ft/sec is approximated by a linear function of 5% increase in temperature rise for every .1 ft/sec decrease in flow. Using this, a Fluid Velocity Multiplier (Mfv) can be created as follows:

Mfv = 1+(1-Fluid Velocity)/2

Specific Heat

Specific heat is a property that measures the temperature rise of a material as it absorbs heat. Generally the higher the value of specific heat for a fluid, the better its heat transfer capability. The specific heat of water is 1.0 and crude oil approximately .5. (Ref 1)

100% oil wells are rare. The majority of ESP installations in the U.S. have oil cuts lower than 10%. For our purposes in establishing a rule of thumb to adjust motor temperature rise relative to oil cut we are going to assume that all ESPs are targeted a 10% oil cut and that temperature rise must be reconsidered when oil cut is above this level.

We are going to develop an Oil Cut Multiplier (Moc) on the consideration that for every percent increase in oil cut beyond 10%, there is a corresponding percent increase in temperature rise. We also assume that below 10% oil cut, the temperature rise is unaffected.

For Oil > 10%

$$\text{Oil Cut Multiplier (Moc)} = 1 + (\text{Oil Cut\%} - 10) / 100$$

PUTTING IT TOGETHER

So far we have developed a Temperature Rise Allowance (TRa) to provide an estimate of the temperature rise available for a motor using class "H" insulation. We have estimated the impact of some of the variables in supplied power, motor loading and fluid heat transfer.

For simplicity many important factors have been left out. The effect of fluid viscosity on heat transfer and the effect of the temperature on the viscosity, increased resistance to heat transfer due to scaling or non uniform cooling from the motor laying against one side of the casing have all been ignored. A more detailed treatment of these factors is avaliable in other litterature (Ref. 5).

To put the model together, one more large assumption has to be made. It will be assumed that these variables do not interact and that they can be simply combined by multiplying them to arrive at an over all estimate of the temperature rise in the motor. The total Temperature Rise Multiplier (Mtr) would be:

$$\text{Temperature Rise Multiplier (Mtr)} = \text{Mol} \times \text{Mmv} \times \text{Mvi} \times \text{Mfv} \times \text{Moc}$$

This multiplier can be used with the design temperature rise (TRd) to make an estimate of the Predicted Temperature Rise (TRp) for the motor.

$$\text{Predicted Temperature Rise (TRp)} = \text{Mtr} \times \text{TRd}$$

With this value and suitable safety factor, we can calculate either a maximum recommended well temperature for a average run life, or we can calculate an average run life for the actual well temperature.

For a maximum well temperature the Predicted Temperature Rise is multiplied by a suitable safety factor and subtracted from the insulation temperature limit

$$\text{Maximum Temperature(Tmax)} = 356 - \text{TRp} \times \text{SF}$$

To estimate the motor life, we need to know the Maximum Temperature (Tmax), the well temperature (Twell) and the motor life under normal conditions. Using the rule of thumb, that insulation life is cut in half for every 18 degrees F that the temperature limit is exceeded, motor is calculated as;

$$\text{Motor Life} = \frac{\text{Normal Life}}{2^{\{(\text{Twell}-\text{Tmax})/18\}}}$$

EXAMPLES

The following examples use the worksheet (Figure 5) which contains a summary of the calculations presented.

Example 1 (Figure 6):

A 1000 volt, 100 Hp Motor, 5.62" OD, rated 250 deg F
Pumping 725 BPD, 15% oil in 7"-23lb casing (6.366 ID)
Voltage is 980, 960, and 970 volts
10 Volt drop in the cable

It is assumed that this motor has a standard life expectancy of two years, a design safety factor of 2 and a rated temperature rise of 53 degrees F.

The temperature rise multiplier is calculated at 1.183. This gives a maximum well temperature of 230 F. If this unit is used in a 230 degree well, there should be no change in the expected run life.

This worksheet can also indicate the results of heavy overload. Using the data in Example 1, the motor is loaded to 150 Hp. The efficiency change goes off the chart, but is estimated to be 80%. Transformers are set so that the motor gets name plate voltage (Mmv = 1). The temperature range multiplier works out to be 2.980 and the maximum well temperature for standard life is 40 degrees F If this motor were to be used in a 230 degree well, the expected run life would be less than a day.

Moderately heavy loads can be used without changing the anticipated run life, if the well temperature is limited.

Example 2 (Figure 7):

Using the data from Example 1, except that the load has been increased to 125 Hp and the voltage correctly set (Mmv = 1), the maximum well temperature calculates to be 200 degrees F.

The new ratings on some ESP motors reflect this type of loading. The application temperature is limited to some number, 180 or 200 degrees F. The output horsepower of these units can then be increased 20 to 30% without harming the run life.

Likewise, if the motors are underloaded, then the maximum well temperature can be increased. If the load in this example was 60 horse power, the maximum well temperature for undiminished life becomes 280 degrees F. If a one year life is acceptable, the maximum well temperature approaches one year.

A example, taken from the literature (Ref 6), can use this worksheet to examine some field problems. This field was difficult to produce and had a large number of motor and cable failures. The average life of the ESP was in the neighborhood of 50 to 80 days. We will assume that the motors were correctly sized and loaded

5.62" OD, rated 250 deg F
Average 1500 BPD, 5% oil in 7" casing (6.366 ID)
Assume fairly well balanced voltage, 980, 960, and 970 volts
Well temperature 234 degrees F

It is assumed that this motor has a standard life expectancy of two years, a design safety factor of 2 and a rated temperature rise of 53 degrees F.

The worksheet shows that the maximum temperature for this motor should be 248 degrees F. It should have no problem in a 234 degrees well. This was not the case. In the paper is was mentioned that the power system had problems and they measured occasional voltage imbalance of 10% to 15%. These imbalances were random and did not last.

To account for this the example is reworked with a voltage that will produce a 10% imbalance:

$$V1 = 980, V2 = 835, V3 = 970$$

For an undimenished life, the calculations indicate a maximum well temperature of 36 degrees F. With a well temperature of 234 degrees, the life of the unit is calculated as 0.34 days. The predictions for 15% imbalance were evem more ridiculous.

The paper goes on to report that most of the short run problems were solved with the installation of a new power sub station and new lines. The indications is that large imbalances, even of short duration can drastically shorten the life of the motor.

CONCLUSION

The main detractor to the life of a ESP motor is the temperature. This paper has summarizes the major factors effecting the temperature rise in an ESP motor. These factors have been presented as implified formulas in the form of a worksheet for estimating either the maximum allowable temperature for a motor, or the life expectancy of a motor at a specific well temperature.

The calculations affirm the logic of re-rating motors to match more closely the environmental temperature in which they will operate.

The worksheet indicate the cautions necessary when working in higher temperature wells and show the influence of the factors.

No claim is made for the accuracy of specific numbers produced by the worksheet. The factors involved temperature rise have been greatly simplified. In corrosive and abrasive condition, the life of the unit may be more dependent on the life of the pump and the sealing section. The results should be useful in comparative decisions.

REFERENCES

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6. Mohrbacher, J.D.: "A Field Study of ESP Performance in a Deep, Hot, and Sour Environment," SPE Paper 12913, presented at the 1984 Rocky Mountain Regional Meeting, Casper Wyoming, May 21-23, 1984.

The worksheet shows that the maximum temperature for this motor should be 248 degrees F.

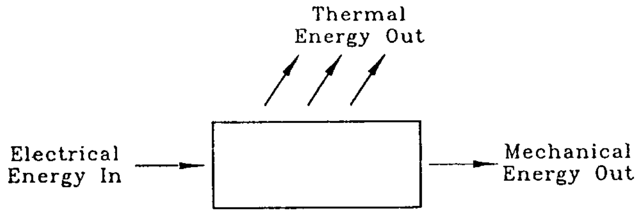

Figure 1 - ESP thermal model

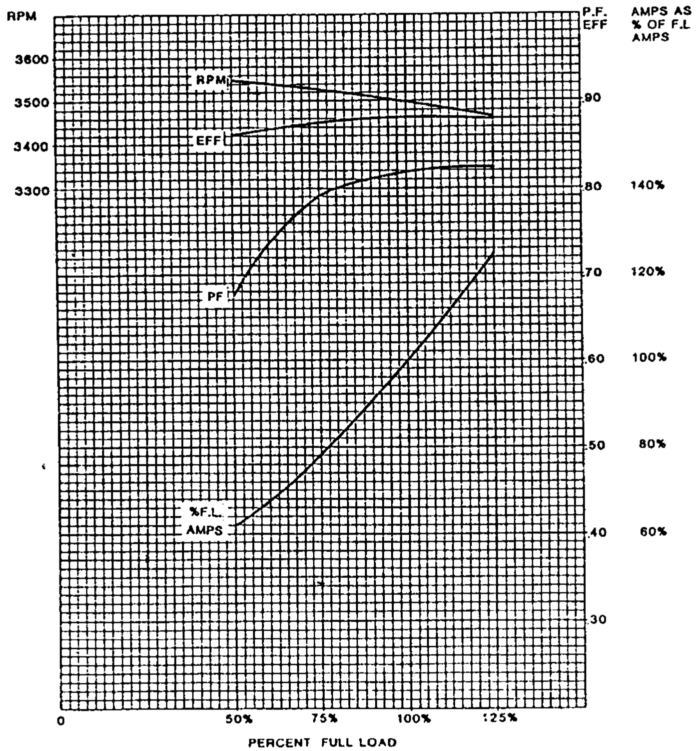

Figure 2 - Motor characteristic curve

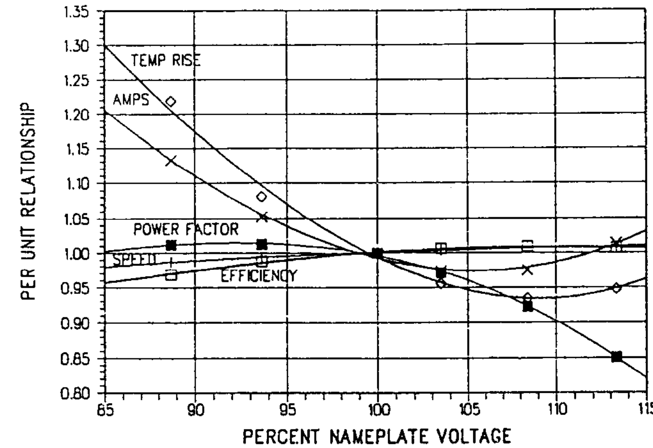

Figure 3 - Typical motor characteristic curve

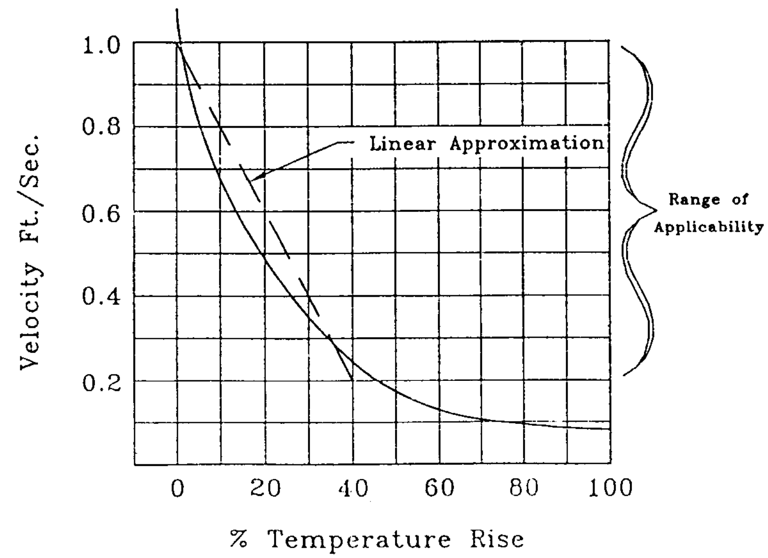

Figure 4

Operating Load Multiplier (Mol):

$$Mol = \frac{Hp_{Act}}{Hp_{Dsg}} x \frac{(1/Eff_{Act}-1)}{(1/Eff_{Dsg}-1)} = \underline{\qquad}$$

Voltage Imbalance Multiplier (Mvi):

$$Vavg = (V1+V2+V3)/3 =$$

$$\%\ Imbal = 100\ x \frac{Max\ Dev}{Vavg} =$$

$$Mvi = 1+\frac{(2\ x\ (\%\ Imbal)^2}{100} = \underline{\qquad}$$

Motor Voltage Multiplier (Mmv):

$$\%\ NP\ Volt = 100x(Vavg-Loss)/Vnp =$$

Mmv = Consult manufactures curves = ____

Fluid Velocity Multiplier (Mfv):

$$Velocity\ (fps) = \frac{.012\ x\ Q(BPD)}{(ID^2-OD^2)} =$$

For fluid velocity > 0.2 fsp and < 1 fps

$$Mfv = 1+\frac{1-Fluid\ Velocity}{2} = \underline{\qquad}$$

Oil Cut Multiplier (Moc):

for Oil > 10%

$$Moc = 1+\frac{Oil\ Cut\%\ -10}{100} = \underline{\qquad}$$

Temperature Range Multiplier (Mtr):

$$Mtr = Mol\ x\ Mmv\ x\ Mvi\ x\ Mfv\ x\ Moc = \underline{\qquad}$$

Actual Temperature Rise (Tra):

$$Tra = Mtr\ x\ Trd = \underline{\qquad}$$

Maximum Well Temperature:

$$T_{Max} = 356 - Tra\ x\ SF = \underline{\qquad}$$

Estimated Motor Life:

$$Life = \frac{Standard\ Life}{2^{[(Twell-Tmax)/18]}} = \underline{\qquad}$$

Figure 5 - Motor rating work sheet

Operating Load Multiplier (Mol):

$$Mol = \frac{Hp_{Act}}{Hp_{Dsg}} x \frac{(1/Eff_{Act}-1)}{(1/Eff_{Dsg}-1)} = \frac{95\ Hp}{100Hp} x \frac{(1/87.0\ -1)}{(1/88.0\ -1)} = \underline{1.04}$$

Voltage Imbalance Multiplier (Mvi):

$$Vavg = (V1+V2+V3)/3 = (980 + 960 + 970)/3 = 970$$

$$\%\ Imbal = 100\ x \frac{Max\ Dev}{Vavg} = 100\ x\ \frac{10}{970} = 1.03$$

$$Mvi = 1+\frac{(2\ x\ (\%\ Imbal)^2}{100} = 1+\frac{2x1.03^2}{100} = \underline{1.02}$$

Motor Voltage Multiplier (Mmv):

$$\%\ NP\ Volt = 100x(Vavg-Loss)/Vnp = (970-10)/1000 = 96\%$$

Mmv = Consult manufactures curves = 1.05

Fluid Velocity Multiplier (Mfv):

$$Velocity\ (fps) = \frac{.012\ x\ Q(BPD)}{(ID^2-OD^2)} = \frac{.012\ x\ 725}{6.366^2-5.62^2} = .979$$

For fluid velocity > 0.2 fsp and < 1 fps

$$Mfv = 1+\frac{1-Fluid\ Velocity}{2} = 1+\frac{1-.979}{2} = \underline{1.01}$$

Oil Cut Multiplier (Moc):

for Oil > 10%

$$Moc = 1+\frac{Oil\ Cut\%\ -10}{100} = 1+\frac{15-10}{100} = \underline{1.05}$$

Temperature Range Multiplier (Mtr):

$$Mtr = Mol\ x\ Mmv\ x\ Mvi\ x\ Mfv\ x\ Moc = \underline{1.184}$$

Actual Temperature Rise (Tra):

Tra = Mtr x Trd   53 x 1.184 = 62.7 Deg. F

Maximum Well Temperature:

$$T_{Max} = 356 - Tra\ x\ SF = 356 - 62.7\ x\ 2 = \underline{230\ Def\ F}$$

Estimated Motor Life:

$$Life = \frac{Standard\ Life}{2^{[(Twell-Tmax)/18]}} = \frac{730}{2^{[(230-230)/18]}} = \underline{730\ Days}$$

Figure 6 - Motor rating work sheet, Example 1

Operating Load Multiplier (Mol):

$$Mol = \frac{Hp_{Act}}{Hp_{Dsg}} x \frac{(1/Eff_{Act}-1)}{(1/Eff_{Dsg}-1)} = \frac{125Hp}{100Hp} x \frac{(1/.87\ -1)}{(1/.88-1)} = \underline{1.367}$$

Voltage Imbalance Multiplier (Mvi):

$$Vavg = (V1+V2+V3)/3 = (980 + 960 + 970)/3 = 970$$

$$\%\ Imbal = 100\ x \frac{Max\ Dev}{Vavg} = 100\ x\ \frac{10}{970} = 1.03$$

$$Mvi = 1+\frac{(2\ x\ (\%\ Imbal)^2}{100} = 1+\frac{2x1.03^2}{100} = \underline{1.02}$$

Motor Voltage Multiplier (Mmv):

$$\%\ NP\ Volt = 100x(Vavg-Loss)/Vnp = 100x(970-10)/970 = 100\%$$

Mmv = Consult manufactures curves = 1..00

Fluid Velocity Multiplier (Mfv):

$$Velocity\ (fps) = \frac{.012\ x\ Q(BPD)}{(ID^2-OD^2)} = \frac{.012\ x\ 725}{6.366^2-5.62^2} = .979$$

For fluid velocity > 0.2 fsp and < 1 fps

$$Mfv = 1+\frac{1-Fluid\ Velocity}{2} = 1+\frac{1-.979}{2} = \underline{1.01}$$

Oil Cut Multiplier (Moc):

for Oil > 10%

$$Moc = 1+\frac{Oil\ Cut\%\ -10}{100} = 1+\frac{15-10}{100} = \underline{1.05}$$

Temperature Range Multiplier (Mtr):

$$Mtr = Mol\ x\ Mmv\ x\ Mvi\ x\ Mfv\ x\ Moc = \underline{1.478}$$

Actual Temperature Rise (Tra):

Tra = Mtr x Trd   53 x 1.478 = 78 Deg. F

Maximum Well Temperature:

$$T_{Max} = 356 - Tra\ x\ SF = 356 - 62.7\ x\ 2 = \underline{200\ Def\ F}$$

Estimated Motor Life:

$$Life = \frac{Standard\ Life}{2^{[(Twell-Tmax)/18]}} = \frac{730}{2^{[(200-200)/18]}} = \underline{730\ Days}$$

Figure 7 - Motor rating work sheet, Example 2