# ECONOMIC CONSIDERATIONS FOR SIZING TUBING AND POWER CABLE FOR ELECTRIC SUBMERSIBLE PUMPS *

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## ABSTRACT

Power consumption of an electric submersible pump installation may be categorized into three components, the energy required to perform useful work which is equivalent to the net hydraulic load divided by the product of pump and motor efficiencies, the energy absorbed by tubing friction which is equal to the dissipated hydraulic energy divided by the efficiency product, and power cable electrical losses. An improved design technique is presented which brings the two preceding categories of energy loss into economic perspective. The interrelated effects of tubing friction, voltage drop and motor voltage on ESP power consumption are demonstrated, as is the degree of desirability for using a motor of the highest available voltage. An equation is developed for calculating power consumption for combinations of tubing size, power cable size and motor voltage, which is useful in making economic evaluations of alternatives. Variations of power consumption are illustrated graphically for various combinations of tubing size, power cable size and motor voltage. Also illustrated is the effect of the nature of a specific net hydraulic load, i.e. the product of rate, lift and specific gravity. Practical examples utilizing the design techniques herein developed are presented and comparisons are made to designs based on common practice.

## INTRODUCTION

Sizing of tubing and power cable for electric submersible pumps (ESP's) has not received attention commensurate with the inherent effects on energy consumption and resultant costs. Common practice is to select sufficiently large tubing so that head loss will not exceed 100 ft per 1,000 ft, and power cable of adequate conductivity to limit voltage drop to 30 V per 1,000 ft. A calculation is also made to determine if the chosen cable permits adequate motor terminal voltage during starting conditions. Under a later topic it is demonstrated that these criteria permit frictional energy losses of up to 10% of net hydraulic load, and dictate electrical energy losses which vary directly with depth cubed and inversely with motor voltage squared. An alternative basis for cable selection limits voltage drop to 5% of motor nameplate voltage[1]. It is herein shown by practical examples that this criteria may not produce a viable design in some circumstances. In many instances, the tubing used in an ESP installation may be that employed in a prior sucker-rod pumping system. An example is presented which demonstrates that this situation could result in a tubing string of superfluous flow capacity, while leaving insufficient clearance for the installation of an adequate power cable. Presently used bases for tubing and power cable selection will normally result in a mechanically functional system, although not necessarily the most economical one at current electric power costs. Furthermore, these bases do not recognize the interrelated effects of tubing friction, power cable resistance and motor voltage on ESP power consumption, nor do they address optimization of equipment selection to produce minimun cost. In succeeding topics the contribution of

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these three factors to power consumption are investigated and a basis for optimum equipment selection is developed.

It has been observed that the selection of power cable is strongly influenced by vendors' quotations for complete ESP systems. Equipment installed on the basis of such proposals should be expected to be functional and relatively trouble free; however, only initial system cost is likely to have been considered in a competitive bidding situation. It is the responsibility of the consumer to determine the combination of cable and tubing sizes which will result in minimum cost operation.

## POWER CONSUMPTION EQUATION

The net hydraulic load of an electric submersible pump represents the specific task for which the system was designed and installed. This quantity equals the product of producing rate, net lift and fluid specific gravity, and the associated power consumption is equivalent to this product divided by pump and motor efficiencies. Total power consumption ($U_T$) of an ESP installation may be separated into three components, the net hydraulic load power requirement ($U_h$), power consumed by tubing friction ($U_f$) which is equal to the dissipated hydraulic energy divided by the product of pump and motor efficiencies, and electrical losses in the power cable ($U_e$). The sum of $U_h$ and $U_f$ equals the total hydraulic load power requirement ($U_H$) which is equivalent to motor input power, and the sum of $U_f$ and $U_e$ represents total power losses ($U_L$) exclusive of the pump and motor efficiency losses attributable to $U_h$. Mathematical expressions for $U_T$, $U_h$, $U_f$, $U_e$, $U_H$ and $U_L$ are developed in Appendix A, as is an expression for normalized total power consumption ($U_N$) defined as $U_T$ divided by $U_h$. Thus $U_N$ represents total power consumption expressed as a multiple of the power applied to the performance of useful work. Therefore, it is indicative of how efficiently power is utilized. A $U_N$ value of 1.0 is equivalent to an efficiency of 100%, exclusive of pump and motor efficiencies, and larger values indicate decreasing efficiencies.

The two terms of total power consumption as expressed in Eq. A-10 are equal to $U_H$ and $U_e$, respectively. The difference between surface tubing pressure ($p_t$) and pump inlet pressure ($p_i$) appears in a parenthetic expression common to each term. The values of these two quantities are generally small compared to the total dynamic head and, furthermore, tend to cancel each other. Therefore, ignoring the effects of these for the purpose of analyzing the effects of all other variables on power consumption does not result in significant error in most circumstances. Thus, for all practical purposes, the first term of $U_T$ is proportional to producing rate (q), fluid specific gravity ($\gamma$), pump setting depth ($D_k$) and ($1000 + H_L$) or ($1000 + Md_t^{-5}$); and inversely proportional to the product of pump and motor efficiencies ($E_p E_m$). The quantity ($Md_t^{-5}$) is a close approximation to head loss ($H_L$). Setting depth was expressed in 1,000 ft units in the derivations of Appendix A because head loss data are commonly presented in ft per 1,000 ft. Likewise, electrical property data of conductors are commonly expressed on a 1,000 ft basis. Applying the preceding analysis to the second term of Eq. A-10 reveals that cable power loss is proportional to $q^2$, $\gamma^2$, $D_k^3$, $(1000 + H_L)^2$ or $(1000 + Md_t^{-5})^2$ and the conductor resistance ($r_k$) or the reciprocal of conductor area ($A_c^{-1}$); and inversely proportional to the squares of motor voltage ($V_m$), power factor ($F_p$), pump efficiency ($E_p$) and motor efficiency ($E_m$). Values of $r_k$ conforming to the recommended maximums[2,3] can be determined from Table 1.

The interrelated effects of tubing friction, power cable resistance and motor voltage on total power consumption become obvious from the preceding discussion, or may be inferred directly from Eq. A-10. The first term of $U_T$ is a function of only one of these three variables. Head loss due to tubing friction appears in the factor $(1000 + H_L)$. The second term is a function of all three variables. Head loss occurs in the same factor as in the first term, however, this factor is squared. Power cable resistance is a direct multiplier of the second term. Most dramatic is the effect of motor voltage, the square of which appears in the denominator. Thus, an increase in motor voltage significantly decreases the value of this term.

An obvious conclusion from the preceding analysis is that the highest available motor voltage is the most desirable. Not only will the use of a higher voltage motor reduce power consumption, in many instances it will result in a smaller size and thus cheaper power cable being the optimum size. An example illustrating this is presented under a subsequent topic. In the case of a new installation the only cost associated with a higher voltage motor would be a somewhat greater investment for a motor controller of adequate voltage rating. An inadequate power distribution system or a restrictive local ordinance would be the only justifiable reasons for not using the highest available voltage motor for a new installation. It has been suggested that high voltage motors lack the longevity of lower voltage motors. This is neither confirmed nor denied, however, even if it were true, instances in which motor insulation life was the ultimate cause of failure would be relatively insignificant. In the case of a replacement motor in an existing installation, a change to a higher voltage might involve investments for replacing transformers and the motor controller. In this event an economic analysis would be required to determine if the resulting power savings would justify the required expenditure.

Effects of the common practice of selecting tubing size based on a maximum head loss of 100 ft per 1,000 ft and selecting power cable based on a maximum voltage drop of 30 V per 1,000 ft may be inferred from the equations of Appendix A. It may be observed from Eqs. A-1 and A-2 that a head loss of 100 ft per 1,000 ft would result in a frictional energy loss of 10% of net hydraulic load. Eq. A-8 indicates that fixed voltage loss criteria, such as 30 V per 1,000 ft, would result in electrical energy losses which vary directly with depth cubed and inversely with motor voltage squared. The preceding observations assume that $p_t$ and $p_i$ are approximately equal or relatively small.

It has been mentioned that both pump and motor efficiencies appear in the denominator of the first term of the power consumption equation (Eq. A-10), and that the squares of the power factor and efficiency product appear in the denominator of the second term. This demonstrates the necessity of operating a pump and motor at conditions of high efficiency and power factor if power consumption is to be minimized. High pump efficiency is assured when a pump is selected that will deliver the design rate at near peak efficiency. Obtaining high motor efficiency and power factor is discussed in the following topic.

## CURRENT, POWER FACTOR AND EFFICIENCIES

Use of the techniques herein presented requires that the running current, power factor, and pump and motor efficiencies be known. Pump efficiencies are readily obtainable from plots of efficiency versus producing rate furnished by pump manufacturers. Current, power factor and motor efficiency depend upon motor loading. Presented in Fig. 1 are typical values of these three variables plotted versus motor load expressed as a percent of full load rating. Current is expressed as percent of full load current in this figure. For design purposes full rated load may be assumed because good design dictates use of a motor that will operate nearly loaded; however, a more precise calculation can be made if specific load conditions are known. Power cable impedance will have a minute effect on current. Motor current, power factor and efficiency data can be obtained for specific motors from the various pump manufacturers. The decline of the latter two of these variables with decreasing loading, as illustrated in Fig. 1, demonstrates the importance of selecting a motor that will operate nearly loaded. The power factor that should be used in the equations of Appendices A and B would be one representing the motor and power cable in series. Inclusion of the power cable impedance results in a power factor improvement of up to approximately 4% because the cable adds considerably more resistance to the circuit than inductive reactance. A sample calculation of this serial power factor is presented in Appendix C.

## MOTOR STARTING EQUATION

Selection of an economical cable size does not necessarily guarantee dependable motor starting. Presented under a subsequent topic is an example of an otherwise optimum ESP system that may not start. A minimum of 50% of nameplate voltage is required at the terminals of most submersible motors to assure starting[2]. Typically inrush current of the order of 3 to 5 times steady state running current occurs the instant a submersible motor is energized. A technique has been presented to calculate starting current.[4] This inrush current results in a power cable voltage drop equivalent to the same 3 to 5 factor times steady state voltage drop. In the case of high horsepower pumps installed at shallow depths minimum motor terminal voltage may not be a problem; however, the inrush current may be so high as to require a motor controller capable of reduced voltage starting to maintain power system stability. Use of these devices and associated problems have been discussed.[5] Other sources of voltage drop during starting include transformer impedance and sag in the primary power system. Starting voltage is commonly calculated by multiplying a starting current factor ($F_{Is}$) times the running cable voltage drop and subtracting this product from the no-load transformer voltage. A sufficiently large value of $F_{Is}$ is normally used to account for all sources of voltage drop. The preceding is the basis for the derivation of Eq. B-1 presented in Appendix B, which is a formula for calculating the fraction of nameplate voltage available for starting ($f_{Vs}$). Eqs. B-3 and B-4 were derived from Eqs. B-1 and A-6 to facilitate plotting the no-start lines of Fig. 2 through Fig. 7, which are discussed in the succeeding topic. These two equations are formulas for conductor voltage drop coefficient ($K_V$) and motor nameplate voltage ($V_m$), respectively, for specified values of $F_{Is}$ and $f_{Vs}$.

## GRAPHICAL ILLUSTRATION OF COMBINED EFFECTS

The combined effects of tubing size, power cable size, and motor voltage on power consumption are illustrated graphically in Fig. 2 through Fig. 7. From these the effect of the nature of a specific net hydraulic load can also be inferred. In the preparation of these six figures, $p_i$ and $p_t$ were assumed to be equal or negligible. Also assumed were values of 0.82 and 0.85 for motor power factor and efficiency, respectively. Pump efficiencies were selected from Table 3. Copper conductors were used and combinations of producing rate and net lift were selected which would result in a constant net hydraulic load throughout this development. Figs. 2, 3 and 4 contain plots of $U_N$ versus conductor area ($A_c$) and AWG size for motor voltages of 1,000 V, 1,300 V, 1,700 V and 2,200 V for combinations of producing rate, net lift and tubing size of respectively 4,000 bbl/D, 2,000 ft and 3.5-in.; 2,000 bbl/D, 4,000 ft and 2.875-in.; and 1,000 bbl/D, 8,000 ft and 2.375-in. Tubing sizes commensurate with flow rates were used in these three examples to suppress the effects of head loss so that the contribution of all other factors would not be obscured. The degree of desirability of using the highest available motor voltage can be observed from each of these three figures. These figures illustrate that the effect of motor voltage is magnified when conductor area diminishes. This could be anticipated from Eq. A-11, as the square of the motor voltage appears in the denominator of the second term and conductor resistance appears in the numerator. Comparing Figs. 2 through 4 illustrates that the need for higher voltage motors becomes progressively greater as the nature of the net hydraulic load shifts to greater depths. It can be observed from Fig. 4 that the power consumption of a system employing a 1,000-V motor installed at a depth of 8,000 ft would be 13% greater than that of one using a 2,200-V motor if AWG size 1 cable is used, and that the use of size 2 or smaller cable would prohibit the starting of a 1,000-V motor under the conditions assumed in this example.

Figs. 5, 6 and 7 contain plots of $U_N$ versus $A_c$ and AWG size for various tubing sizes and for the same values of producing rate and net lift upon which Figs. 2, 3 and 4, respectively, were based. A constant motor voltage of 1,300 V was used in the preparation of Figs. 5, 6 and 7 so that the effects of motor voltage would be suppressed, thus allowing the effects of tubing size, conductor size, and the nature of the net hydraulic load on power consumption to be more easily distinguished. A pronounced effect of tubing size on power consumption is demonstrated in Fig. 5. Under the conditions assumed in this example of 4,000 bbl/D and 2,000 ft net lift, the power consumption using 2.375-in. tubing is 30% more than if 4.5-in. tubing were used, assuming AWG size 2 cable is installed. Significant effects of tubing size are also present at the 2,000 bbl/D producing rate and 4,000 ft net lift depicted in Fig. 6; however, the effect of tubing size over the entire range from 2.375-in. to 4.5-in. is minimal under the conditions presented in Fig. 7 of 1,000 bbl/D producing rate and 8,000 ft net lift.

No-start lines are traced on Figs. 2, 3, 4, 6 and 7. For Fig. 5 the no-start line fell outside the depicted area. The no-start lines of Figs. 2, 3 and 4 are the loci of marginal starting points for assumed motor voltages and for the tubing size designated on the respective figures. In an extension of Fig. 5 and in Figs. 6 and 7 the no-start lines are the loci of marginal starting points for an assumed voltage of 1,300 V and for various tubing sizes. The $U_N$ versus $A_c$ curves become dashed lines after intersecting the no-start lines of all figures, indicating that motor starting will likely be a problem. The no-start lines of Figs. 2, 3 and 4 were plotted by assuming various cable sizes and determining values of $r_k$ and $K_V$ from table 1. Eq. B-4 was then used to calculate corresponding values of $V_m$ for marginal starting conditions. These were substituted into Eq. A-11 along with a value of $H_L$ representative of the tubing size designated on the respective figures, to calculate values of $U_N$ corresponding to each assumed cable size. Values of 4.0 and 0.5 were assumed for $F_{Is}$ and $f_{Vs}$, respectively, in the preparation of all six figures. The no-start lines of Figs. 6 and 7 were plotted by calculating values of $U_H$ for each tubing size using Eq. A-3 and substituting these and the assumed motor voltage of 1,300 V into Eq. B-3 to calculate values of $K_V$ at marginal starting conditions. Corresponding values of $A_c$ and $r_k$ were then interpolated from Table 1. Values of $r_k$ and $H_L$ were then substituted into Eq. A-11 to obtain values of $U_N$ corresponding to the interpolated values of $A_c$ for each tubing size.

DESIGN PROCEDURE USING POWER CONSUMPTION EQUATION

It can be inferred from Eq. A-10 that an ESP could achieve a minimum power consumption approaching $U_h$ if sufficiently large casing was installed to permit installation of very large tubing and power cable. It is likely that such an installation would be neither mechanically nor economically feasible; however, the optimization procedure herein presented for an existing well could be extended to include the drilling and completion of a well to be equipped with an ESP system designed for specific conditions. The design procedure outlined below and illustrated in the flow chart presented in Fig. 8 considers both investment and operating costs. Necessary data include a knowledge of well performance, well casing size and weight, completion interval, produced fluid specific gravity, surface tubing pressure, unit power cost and equipment prices.

Proper application of the power consumption equation will result in the most economical ESP system for performing any specific job. As is standard procedure, a pump of the largest series that will fit inside the well casing and deliver the design producing rate at near peak efficiency is selected. The smallest tubing size which will result in a head loss of less than 100 ft per 1,000 ft is tentatively selected. Tubing of smaller diameter and lesser joint strength than 2.375-in. 4.70-lbm/ft J-55 upset should be avoided if possible. Each tubing string considered must have adequate tensil strength to support its own weight, that of the cable, and the hydraulic force. A tentative pump and motor design is next developed in the normal manner using a value of $H_L$ corresponding to the design producing rate and tubing size, appropriate values for $p_i$, $p_t$, and $\gamma$, and a knowledge of well productivity. A motor of the highest available voltage should be selected. Next a power cable of adequate ampacity is tentatively selected which will fit in the clearance between the casing internal diameter and the tubing coupling outside diameter and that will result in a voltage drop of less than 30 V per 1,000 ft if feasible, or otherwise the smallest possible volatage drop. Maximum cable size for various combinations of tubing and casing have been recommended.[1] Voltage drop per 1,000 ft is equal to the product $IK_V$. Values of $K_V$ can be observed for a conductor temperature of 140°F or calculated for other temperatures using Table 1. Recommended maximum ampacities[2,3] are presented in Table 2. The cost of the entire installation can then be calculated. The next step is to calculate the power consumption of this system using Eq. A-10. Using this quantity and the unit power cost, the annual power cost can be computed. The foregoing procedure should be repeated using the next larger cable size. The additional investment for the larger cable should then be divided by the resulting reduction in annual power cost to determine the capital recoupment period. If the result is less than approximately 3 years, the next larger cable size should be tentatively selected and the procedure repeated. These iterations should be continued until an increase in cable size no longer results in an acceptable payout. The largest cable that provided such a payout over the preceding smaller size is the one of choice. Cables smaller than the initial selection need be considered only if the first comparison does not show an acceptable payout. More rigorous economic analyses than that presented above could be developed; however, the effort might not be warranted. Prediction of cable life would be essential for such analyses. A reasonable cable life under average well conditions might be 10 years. However, elevated temperatures and pressures and the presence of hydrogen sulphide can drastically reduce cable life; likewise mishandling and other sources of mechanical damage. Consequently predicting cable life is subject to considerable uncertainty. Determining tubing life would also be necessary but would not be as critical because it would normally be a longer, more easily predicted period.

Up to this point the most economical size cable has been determined for only the initial tentatively selected tubing size. The next larger tubing size should now be selected and the entire procedure outlined above repeated, including the determination of the number of pump stages and motor horsepower. As before, adequate clearance within the casing is essential. The most economical design incorporating the larger size tubing will always be more expensive than the one using the smaller size. The additional investment should be compared to the resulting annual power cost savings as done previously. If a capital recoupment period of less than 3 years is evident, the next larger tubing size should be similarly investigated. Since the initially considered tubing size was the smallest that would result in a head loss of less than 100 ft per 1,000 ft, there is no need of analyzing systems using tubing of smaller diameter. This can be inferred from examination of Eq. A-10 and is demonstrated in Case 1 of the practical examples herein presented.

The preceding described technique should result in an optimum design for any ESP application. However, as with other methods of equipment selection, motor starting must be examined. Eq. B-1 should be used to determine if motor terminal voltage will be adequate at starting conditions. A value of $f_{Vs}$ exceeding 0.5 assures dependable starting.

PRACTICAL EXAMPLES

Utility of the techniques herein developed has been demonstrated in 7 practical examples. Design criteria for these examples has been chosen so that the results will illustrate various points made in previous sections. A minimal power cost of $0.05 per kW-hr has been assumed in all cases. Power costs exceeding twice this amount are common and would greatly magnify the results of these examples. The first three cases were the basis of the graphical illustrations presented in Figs. 2 through 7. The assumption that $p_i$ and $p_t$ were equal or negligible was made for simplicity. Average conductor temperatures of 140°F were assumed in all examples except Case 7. Fluid specific gravities of 1.0 were assumed, except in Cases 5, 6 and 7. Casing internal diameter was not a constraint in Cases 1, 2, 3 and 4 which involved wells completed with 7-in. casing. Cases 5, 6, and 7 employed 5.5-in. casing. Data on the typical pumps and motors from which selections were made are illustrated in Tables 3 and 4, respectively. Presented in Table 5 are typical prices of tubing and power cable which were used in the examples. Total system costs presented in the various cases are for pump, motor, cable and tubing only. Tubing and cable selection would have minimal effect on the cost of other components. These examples illustrate that the designs based on the technique herein presented will generally differ from designs based on commonly used rules or the criteria of reference 1. Table 6 compares the results using these three bases for all 7 cases.

### Case 1 (High Rate/Shallow Depth)

The first three cases are based on identical net hydraulic loads. Case 1 presents a combination of a relatively large producing rate of 4,000 bbl/D and a relatively shallow depth of 2,000 ft. These are the conditions on which Figs. 2 and 5 are based. The first step in designing an ESP system is to select an appropriate type pump. For this application a 7.0-4000 pump was selected. This pump which was designed for installation inside 7-in. casing or larger, develops 36 ft of head per stage at a producing rate of 4,000 bbl/D and requires 1.559 hp (1.163 kW) per stage when pumping at these conditions, assuming $\gamma$ equals 1.0. The smallest diameter tubing that would result in a head loss of less than 100 ft per 1,000 ft was tentatively selected. This criteria dictated using 3.5-in. tubing which is the largest size recommended[1] for installation inside 7-in. casing, and which develops a head loss of 48 ft per 1,000 ft. For the first trial a size 6 cable was investigated. From Table 1 values for $r_k$ and $K_V$ at 140°F equal to 0.489 and 0.744, respectively, may be observed. The first iteration resulted in a system costing $39,340 incorporating a 58-stage, type 7.0-4000 pump and a 100-hp(74.6-kW)/1700-V/36-A type 7.0 motor. Voltage drop per 1,000 ft is the product of running amperage and $K_V$, which in this trial equals 26.8 V per 1,000 ft. Consequently, size 6 cable would be selected if the commonly used criteria of 30 V per 1,000 ft were employed. Using Eq. A-10 a value for $U_T$ of 82.7574 kW can be computed for this initial design. Size 4 cable was next investigated which resulted in an additional cost of $1,200 and a value of $U_T$ of 81.6222 kW, representing a 1.1352 kW decrease. Assuming a power cost of $0.05 per kW-hr, the additional cost of the size 4 cable would be recouped in a period of 2.41 years. Thus, size 4 is preferable compared to size 6, which would have commonly been selected. Use of size 2 cable was similarly investigated and the recoupment period was found to be 9.21 years. Therefore, 3.5-in. tubing and size 4 cable is the optimum combination for Case 1. Application of Eq. B-1 indicates that motor starting is not a problem. The criteria of reference 1 would have dictated the use of size 8 cable, if available.

It was previously stated that it is unnecessary to investigate smaller tubing sizes if the initial selection was the smallest size which develops a head loss less than 100 ft per 1,000 ft. This statement was verified for Case 1. A system utilizing 2.875-in. tubing would result in a head loss of 120 ft per 1,000 ft, an initial cost savings of $2,480, and a power consumption of 87.3752 kW, representing an increase of 5.7530 kW. Assuming a power cost of $0.05 per kW-hr, the additional cost of the system using 3.5-in. tubing would be recouped in a 0.98-year period.

### Case 2 (Medium Rate/Medium Depth)

Case 2 illustrates an ESP producing 2,000 bbl/D from a depth of 4,000 ft. This medium rate, medium depth case was the basis for Figs. 3 and 6. A type 7.0-2000 pump was selected which develops 40 ft of head per stage when operated at a rate of 2,000 bbl/D and absorbs 0.920 hp (0.686 kW) per stage. The initial tubing selection for this example was 2.375-in. which would result in a head loss of 95 ft per 1,000 ft. The most economical design employing this tubing size required a 110-stage pump and a 100-hp(74.6-kW)/1700-V/36-A type 7.0 motor which was slightly overloaded, utilized size 4 cable, consumed 93.2335 kW and cost $47,400. The second tubing selection was 2.875-in. which developed a head loss of 35 ft per 1,000 ft. The most economical design subsequently developed required a 104-stage pump, utilized size 4 cable, consumed 87.8751 kW and cost

$50,240. A system using 3.5-in. tubing which incurred a head loss of 13 ft per 1,000 ft was similarly developed. This design required a 101-stage pump, utilized size 4 cable, consumed 85.9177 kW and cost $56,060. The system employing 2.875-in. tubing and size 4 cable was found to be the optimum. The incremental cost compared to the system employing 2.375-in. tubing would be recouped in a 1.21-year period, assuming a power cost of $0.050 per kW-hr. A power cost of $0.113 per kW-hr would be required to justify the system using 3.5-in. tubing. Application of Eq. B-1 indicates that motor starting would not be a problem for the selected system. By comparison, common practice would have dictated using 2.375-in. tubing and size 6 cable, which would have resulted in a voltage drop of 26.8 V per 1,000 ft. The additional cost of the optimum system compared to that selected by common practice would have been recouped in a period of 1.49 years. Size 4 cable would have been selected if the criteria of reference 1 were used.

Case 3 (Low Rate/Great Depth)

An ESP producing 1,000 bbl/D from a depth of 8,000 ft is illustrated in Case 3. This low rate, deep application was the basis for Figs. 4 and 7. A type 5.5-1000 pump was selected which develops 20 ft of head per stage when operated at a rate of 1,000 bbl/D and consumes 0.254 hp (0.189 kW) per stage. The smallest size tubing commonly used in ESP applications is 2.375-in. Head loss of this size is 26 ft per 1,000 ft at the design rate. Consequently it was chosen for the first trial design. The most economical system employing 2.375-in. tubing required a 411-stage pump and a 100-hp(74.6-kW)/1700-V/36-A type 7.0 motor which was slightly overloaded, utilized size 4 cable, consumed 101.5222 kW and cost $78,752. The next trial used 2.875-in. tubing which developed a head loss of 10 ft per 1,000 ft. The most economical design using this tubing size required a 404-stage pump and the same motor as the previous trial, utilized size 4 cable, consumed 99.7312 kW and cost $84,928. A period of 7.87 years would be required to recoup the additional cost of the system employing the larger tubing, assuming a power cost of $0.05 per kW-hr. Consequently a system utilizing 2.375-in. tubing and size 4 cable would be optimum. Dependable starting was verified using Eq. B-1. Common practice would have dictated using the same size tubing with size 6 cable which would have resulted in a voltage drop of 26.8 V per 1,000 ft. The additional cost of size 4 cable compared to size 6 would have been recouped in a period of 2.02 years. The criteria of reference 1 would dictate using size 1 cable which would not be an economically viable design.

Case 4 (Effect of Motor Voltage on Cable Selection)

The conditions of Case 4 are identical to those of Case 2, and include the use of 2.875-in. tubing which was found to be the optimum size. In Case 2 a 1700-V motor was utilized and it was determined that size 4 cable was the optimum size, assuming a power cost of $0.050 per kW-hr. Power consumption of this system was 87.8751 kW. In order to provide a 3-year recoupment period for the incremental cost of size 2 cable, the power cost would have needed to be $0.143 per kW-hr. Case 4 assumes that an 850-V motor is used. In this circumstance using size 4 cable would result in a power consumption of 99.6816 kW, compared to 94.3444 kW for size 2 and 92.2510 kW for size 1. Size 1 was found to be the optimum in this instance providing a 2.62-year recoupment period for the incremental cost compared to size 2, thus illustrating the effect of motor voltage on the choice of power cable.

Case 5 (Casing Internal Diameter Constraint)

Installing the selected equipment in the wellbores of the previous examples should present no problems. Frequently, however, the internal diameter of the well casing becomes a constraint. Presented in Case 5 is an ESP installation that has inherited a tubing string from the prior sucker-rod pumping system. It is desired to produce 750 bbl/D from a depth of 6,500 ft. Specific gravity of the well fluid is 1.05. The well is equipped with 5.5-in., 17-lbm/ft casing and 2.875-in. external upset tubing. The casing internal diameter is 4.892 in. and the tubing coupling outside diameter is 3.688 in., leaving a clearance of 1.204 in. for a power cable. Using the specified casing and 2.875-in. external upset or non-upset tubing, the largest recommended round cable is size 6.[1] A full length flat cable of larger size could be run; however, this should be done only in rare circumstances as a last resort because of an inherent voltage imbalance. An ESP system was designed using the existing tubing which consisted of a 262-stage type 5.5-0750 pump, a 70-hp(52.2-kW)/1150-V/38-A type 5.5 motor and size 6 cable. Total system cost was $66,722, including the value of the tubing. Cable voltage drop was 28.3V per 1,000 ft and system power consumption was 68.9473 kW. Next a system employing 2.375-in. tubing was designed which consisted of a 264-stage pump, the same motor as before and size 4 cable, which was determined to be the most economical. This system cost $65,484 and resulted in a power consumption of 65.8538 kW. Assuming the two tubing strings involved in this comparison were of new equipment value, the system employing 2.375-in. tubing would have a $1,238 lower initial cost and cost $1,355 per year less to operate than the alternative system. Thus, it has been demonstrated that salvaging the tubing of the prior sucker-rod pump system resulted in an installation of superfluous flow capacity and insufficient current carrying capacity. Common practice would have dictated a system employing 2.375-in. tubing and size 6 cable. Compared to this system the additional cost of the recommended optimum would be recouped in a period of 2.30 years. The criteria of reference 1 would dictate using size 1/0 cable which is neither commonly available nor economically viable.

Case 6 (Tubing/Cable Compromise)

In the preceding example it was obvious which of the two alternative systems was most desirable. This is not always the case. Case 6 involves the same conditions presented in Case 5, except that the well has now responded to enhanced recovery and is capable of producing 1,500 bbl/D. At this rate the head loss of 2.375-in. and 2.875-in. tubing is 56 ft per 1,000 ft and 21 ft per 1,000 ft, respectively. The most economical system employing 2.375-in. tubing consisted of a 361-stage type 5.5-1500 pump, a 130-hp(96.9-kW)/2200-V/31-A motor and size 4 cable. This system cost $84,574 and consumed 126.0527 kW. A system using 2.875-in. tubing was restricted to size 6 cable, included a 349-stage pump and the same motor as the preceding design, cost $85,466, and consumed 125.9265 kW. The system employing 2.375-in. tubing is the one of choice because the recoupment period for the additional cost of the alternative system would be 16.14 years. The point illustrated here is that the power consumption advantage afforded by the larger cable size in Case 5 has been essentially balanced by an increase in energy consumed by tubing friction, as the flow rate increased from 750 bbl/D to 1,500 bbl/D. At a slightly greater rate the two designs would have equivalent economic impact, and at rates above that point the use of 2.875-in. tubing would be the economic choice. This illustrates the compromise that can occur as a result of casing internal diameter constraint.

## Case 7 (Verification of Motor Starting)

It has been stated that the selection of the most economical cable size does not necessarily assure dependable motor starting. Factors contributing to this circumstance include low power cost and deep pump setting depth. This point is demonstrated in Case 7, which concerns a well equipped with 5.5-in. casing and producing 600 bbl/D from 11,000 ft. The well fluid has a specific gravity of 0.9 and the average conductor temperature is 176°F. Using Table 1 values for $r_k$ of 0.522, 0.329 and 0.212 and values for $K_V$ of 0.792, 0.512 and 0.340 can be calculated for sizes 6, 4 and 2 cable, respectively, at this temperature. It becomes quickly apparent that 2.375-in. tubing should be used. Equipment selected for this application include a 427-stage type 5.5-0600 pump and an 80-hp(59.7-kW)/1300-V/39-A type 5.5 motor. Power consumption for this system utilizing sizes 6, 4 and 2 cable is 87.5944 kW, 80.8400 kW and 76.4487 kW, respectively. The incremental cost of size 4 cable compared to size 6 would be recouped in a period of 2.23 years. The recoupment period for the additional cost of size 2 cable over size 4 is 8.01 years. Size 4 is the economic optimum size cable; however, dependable motor starting must be verified. Using Eq. B-1 and assuming a value for $F_{Is}$ of 4, it was determined that $f_{Vs}$ equals 0.49, which is slightly below the threshold value for dependable motor starting. This occurred regardless of the fact that a high voltage motor was used and the optimum size cable was selected. Use of size 2 cable would result in a value of $f_{Vs}$ of 0.66, thus assuring dependable starting. Under the circumstances presented in this example, the starting characteristics of the specific motor should be investigated before cable selection.

## EVALUATING QUOTATIONS

After well productivity has been analyzed and a tubing size selected, it is common practice to solicit competitive bids for the balance of the equipment required for a new ESP installation. Assuming all proposed pumps and motors have approximately the same efficiencies, Eq. A-4 can be used to make a quick comparison of operating costs of various quoted systems. This is true because values of $U_H$ would be approximately the same and the only other component of $U_T$ is $U_e$. A small sample of recent quotations was analyzed and approximately 50% of these proposed the size cable that would have been selected by employing the technique herein presented, while the other 50% proposed a cable which was one size smaller. All quoted systems should have functioned satisfactorily. The quotations incorporating smaller cable were less expensive than the competing bids; however, they were not the economic choice. This demonstrates that it is the consumer's responsibility to determine the combination of cable and tubing sizes which will result in minimum cost operation.

## CONCLUSIONS

A summary of the principal conclusions developed herein follows:

1. Standard bases for tubing and power cable selection do not assure economical systems at current electric power costs.

2. Optimum ESP design requires concurrent evaluation of tubing and power cable sizes and a knowledge of motor voltage availability because of the interrelated effects of tubing friction, power cable voltage drop and motor voltage on power consumption.

3. Motors having the highest available nameplate voltage are the most desirable, and this desirability is magnified at greater depths and when smaller size cable is used.

4. Minimizing power consumption requires operating a pump and motor at conditions of high efficiency and power factor.

5. Changing motor voltage can alter the optimum power cable size.

6. Selection of ESP systems based on the optimization technique herein presented or on commonly used design criteria does not necessarily guarantee dependable motor starting.

7. Using the size tubing required for a replaced sucker-rod pumping installation may result in an ESP system of superfluous flow capacity and insufficient current carrying capacity when casing internal diameter becomes a constraint.

8. Power cable specified in competitive bids is likely to have been selected only on the basis of functionality and initial price.

9. Economic design of ESP systems is the responsibility of the consumer.

<u>NOMENCLATURE</u>

$A_c$ - Conductor area, circular mils

$d_t$ - Tubing internal diameter, in.

$D_k$ - Pump setting depth, 1,000 ft

$E_m$ - Motor efficiency, fractional

$E_p$ - Pump efficiency, fractional

$f_{Vs}$ - Fraction of nameplate voltage available for starting, fractional

$F_{Is}$ - Starting current factor, dimensionless

$F_p$ - Power factor, fractional

$H_L$ - Head loss, ft/1,000 ft

I - Steady state running current, A

$K_V$ - Voltage drop coefficient for a 3-phase system for a specific conductor size, composition and temperature, and at a specific power factor, V/A/1,000 ft

M - Coefficient for specific fluid properties and flow rate

$p_i$ - Pump inlet pressure, psi

$p_t$ - Surface tubing pressure, psi

$q$ - Pumping rate, bbl/D

$r$ - Resistance, Ω

$r_k$ - Conductor resistance, Ω/1,000 ft

$T$ - Temperature, °F

$U_e$ - Power loss in cable, kW

$U_f$ - Power consumed by tubing friction, kW

$U_h$ - Power required for net hydraulic load, kW

$U_H$ - Power required for total hydraulic load, kW

$U_L$ - Combined power loss due to tubing friction and cable resistance, kW

$U_N$ - Normalized total power consumption, dimensionless

$U_T$ - Total power consumption, kW

$V_m$ - Motor nameplate voltage, V

$X$ - Inductive reactance, Ω

$X_k$ - Cable inductive reactance, Ω/1,000 ft

$Z$ - Impedance, Ω

$\theta$ - Phase angle between applied voltage and current or $\cos^{-1}F_p$, deg

$\gamma$ - Fluid specific gravity, dimensionless

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REFERENCES

1. API RP 11U: "API Recommended Practice for Sizing and Selection of Electric Submersible Pumps," First Edition, June 20, 1984.

2. IEEE Std 1018-1985: "IEEE Recommended Practice for Specifying Electric Submersible Pump Cable/Ethylene Propylene Rubber Insulation," Dec. 18, 1984.

3. IEEE Std 1019-1985: "IEEE Recommended Practice for Specifying Electric Submersible Pump Cable/Polypropylene Insulation," Dec. 18, 1984.

4. Vandevier, J. E.: "Procedure for Calculating Motor Starting Conditions for Electric Submersible Pump Installations," Presented at the 1985 SPE Gulf Coast Local Section ESP Workshop, April 9-10, 1985.

5. Hyde, R. L. and Brinner, T. R.: "Starting Characteristics of Electric Submergible Oil Well Pumps," IEEE Trans. Vol. IA-22, No. 1 (Jan./Feb. 1986) 133-44.

6. Marks, Lionel S.: "Mechanical Engineers Handbook," 1958, 6th Edition, McGraw-Hill Book Co., Inc.

## APPENDIX A - DERIVATION OF POWER CONSUMPTION EQUATION

### Power Required for Net Hydraulic Load

The rate of performing useful work (net hydraulic load) equals the product of producing rate, net lift and fluid density. Electric power required for the net hydraulic load is this product divided by both pump and motor efficiencies as expressed below.

$$U_h = \frac{1.268x10^{-5} q(p_t - p_i + 433\gamma D_k)}{E_p E_m} \quad \text{. . . . . . . . . . . . . . . (A-1)}$$

### Power Consumed by Tubing Friction Loss

Tubing friction loss data is commonly presented in ft/1,000 ft. The product of this value, pump setting depth expressed in thousands of feet, producing rate, and fluid density equals the frictional load. Electric power required is this product divided by both pump and motor efficiencies as expressed in Eq. A-2.

$$U_f = \frac{1.268x10^{-5} q(0.433\gamma D_k H_L)}{E_p E_m} \quad \text{. . . . . . . . . . . . . . . . . . . (A-2)}$$

### Total Hydraulic Load

The total hydraulic load is the sum of the net hydraulic load and frictional load. The resultant power requirement represents the motor input power and is expressed in Eq. A-3, which was obtained by adding Eqs. A-1 and A-2.

$$U_H = \frac{1.268x10^{-5} q[p_t - p_i + 0.433\gamma D_k(1000 + H_L)]}{E_p E_m} \quad \text{. . . . . . . . (A-3)}$$

### Power Cable Loss

Power cable loss in a balanced 3-phase system can be expressed as follows.

$$U_e = 3x10^{-3} D_k I^2 r_k \quad \text{. . . . . . . . . . . . . . . . . . . . . . (A-4)}$$

Motor input power (Eq. A-3) can be expressed as follows.

$$U_H = \sqrt{3}x10^{-3} V_m I F_p \quad \text{. . . . . . . . . . . . . . . . . . . . . . . (A-5)}$$

Eq. A-6 is Eq. A-5 solved for I.

$$I = \frac{U_H x10^3}{\sqrt{3}V_m F_P} \quad \text{(A-6)}$$

Combining Eqs. A-4 and A-6 shows the relationship between $U_e$ and $U_H$.

$$U_e = \frac{D_k r_k U_H^2 x10^3}{V_m^2 F_P^2} \quad \text{(A-7)}$$

Eq. A-8 is a more detailed expression for $U_e$, and was derived by substituting the value of $U_H$ from Eq. A-3 into Eq. A-7.

$$U_e = \frac{1.608x10^{-7} D_k r_k q^2 [p_t - p_i + 0.443\gamma D_k(1000 + H_L)]^2}{V_m^2 F_P^2 E_p^2 E_m^2} \quad \text{(A-8)}$$

Combined Power Loss

The following expression for both tubing friction and cable resistance power losses was developed by adding Eqs. A-2 and A-8.

$$U_L = \frac{1.268x10^{-5} q(0.433\gamma D_k H_L)}{E_p E_m} + \frac{1.608x10^{-7} D_k r_k q^2 [p_t - p_i + 0.433\gamma D_k(1000 + H_L)]^2}{V_m^2 F_P^2 E_p^2 E_m^2} \quad \text{(A-9)}$$

Power Consumption Equation

Total power consumption is the sum of $U_h$, $U_f$ and $U_e$, $U_H$ and $U_e$, or $U_h$ and $U_L$. Eq. A-10 was obtained by adding Eqs. A-3 and A-8.

$$U_T = \frac{1.268x10^{-5} q[p_t - p_i + 0.433\gamma D_k(1000 + H_L)]}{E_p E_m} + \frac{1.608x10^{-7} D_k r_k q^2 [p_t - p_i + 0.433\gamma D_k(1000 + H_L)]^2}{V_m^2 F_P^2 E_p^2 E_m^2} \quad \text{(A-10)}$$

Normalized Power

Normalized total power consumption is defined as $U_T$ divided by $U_h$. Therefore, Eq. A-11 was developed by dividing Eq. A-10 by Eq. A-1.

$$U_N = \frac{p_t - p_i + 0.433\gamma D_k(1000 + H_L)}{p_t - p_i + 433\gamma D_k} + \frac{1.268x10^{-2} D_k r_k q[p_t - p_i + 0.433\gamma D_k(1000 + H_L)]^2}{V_m^2 F_P^2 E_p E_m (p_t - p_i + 433\gamma D_k)} \quad \text{(A-11)}$$

## APPENDIX B - DERIVATION OF MOTOR STARTING EQUATION

A minimum of 50% of nameplate voltage is required at the motor terminals to assure dependable starting.[1] An inrush current equivalent to 3 to 5 times steady state running current occurs the instant a submersible motor is energized, resulting in a cable voltage drop equal to $F_{Is}D_kK_VI$. Since the no-load voltage would have been preadjusted to a level equal to $V_m + D_kK_VI$, the following equation describes the fraction of nameplate voltage available for starting, ignoring transformer impedance losses and sag in the primary system.

$$f_{Vs} = 1 - \frac{D_kK_VI(F_{Is} - 1)}{V_m} \quad \text{(B-1)}$$

Substituting the value of I expressed in Eq. A-6 into Eq. B-1 yields the following:

$$f_{Vs} = 1 - \frac{U_HD_kK_V(F_{Is} - 1)x10^3}{\sqrt{3}V_m^2F_P} \quad \text{(B-2)}$$

Eq. B-3 was obtained by solving Eq. B-2 for $K_V$.

$$K_V = \frac{\sqrt{3}x10^{-3}(1 - f_{Vs})V_m^2F_P}{U_HD_k(F_{Is} - 1)} \quad \text{(B-3)}$$

Eq. B-4 was obtained by solving Eq. B-2 for $V_m$.

$$V_m = \left[\frac{U_HD_kK_V(F_{Is} - 1)x10^3}{\sqrt{3}F_P(1 - f_{Vs})}\right]^{0.5} \quad \text{(B-4)}$$

## APPENDIX C - SAMPLE CALCULATION OF SERIAL POWER FACTOR

A 100-hp(74.6-kW)/1150-V/56-A motor is to be set at a depth of 4,000 ft and operated fully loaded. Motor power factor at full load is 0.81. Size 4 copper cable is to be used. What is the system power factor?

### Analysis of Motor Impedance to Neutral

$Z = V_m/I\sqrt{3} = 1150/56\sqrt{3} = 11.856\Omega$ $\cos\theta = 0.81$ $\sin\theta = 0.5864$

$r = 11.856 \times 0.81 = 9.604\Omega$ $X = 11.856 \times 0.5864 = 6.952\Omega$

### Calculation of Cable Resistance and Reactance

$r = 4 \times r_k = 4 \times 0.308 = 1.232\Omega$ $X = 4 \times X_k = 4 \times 0.0399 = 0.160\Omega$

### Calculation of System Power Factor

$r = 9.604 + 1.232 = 10.836\Omega$ $X = 6.952 + 0.160 = 7.112\Omega$

$\theta = \tan^{-1}(7.112/10.836) = 33.278°$ $F_P = \cos\theta = 0.836$

Thus, the cable impedance resulted in a system power factor which exceeded the motor power factor by 0.026, or 3.21%.

## Table 1
## Typical Copper Power Cable Properties

| AWG Size | Conductor Area ($A_c$) Circular Mils | *Resistance ($r_k$) at 140°F (Ω/1000 ft) | %Inductive Reactance ($X_k$) at 60 Hz, (Ω/1000 ft) | @Voltage Drop Coefficient ($K_v$) at 140°F (V/A/1000 ft) |
|---|---|---|---|---|
| 8 | 16,510 | 0.781 | 0.0459 | 1.167 |
| 6 | 26,240 | 0.489 | 0.0427 | 0.744 |
| 4 | 41,740 | 0.308 | 0.0399 | 0.481 |
| 2 | 66,360 | 0.199 | 0.0362 | 0.321 |
| 1 | 83,690 | 0.158 | 0.0352 | 0.261 |
| 1/0 | 105,600 | 0.126 | 0.0341 | 0.214 |
| 2/0 | 133,100 | 0.101 | 0.0332 | 0.177 |

* Values of $r_k$ at other conductor temperatures (T) can be calculated by multiplying the tabulated data by the factor [1 + 0.0019(T - 140)], from reference 6, page 15-7. Resistances presented here correspond to the maximum allowed by References 2 and 3. A correlation of conductor temperature with well temperature and current has been made.[1]

% To obtain values of $X_k$ at other frequencies multiply the tabulated data by the quotient of frequency/60.

@ Voltage drop coefficients ($K_v$) were calculated assuming a power factor ($F_p$) of 0.83, a temperature of 140°F and a frequency of 60 Hz. Values of $K_v$ at other power factors and for conditions other than 140°F and 60 Hz can be calculated with the formula: $K_v = \sqrt{3}(r_k \cos\theta + X_k \sin\theta)$.

## Table 2
## Copper Conductor Ampacity Ratings

| AWG Size | Ampacity Rating: Polypropylene Insulation | E-P Rubber Insulation |
|---|---|---|
| 1 | 94 | 110 |
| 2 | 82 | 94 |
| 4 | 61 | 70 |
| 6 | 46 | 53 |

## Table 3
## Pump Data Used in Practical Examples

| PUMP TYPE | OPERATING RATE (BBL/D) | SINGLE STAGE PERFORMANCE AT OPERATING RATE HEAD (FT) | EFFICIENCY (%) | *BRAKE HORSEPOWER | AVERAGE COST PER STAGE ($) |
|---|---|---|---|---|---|
| 5.5-0600 | 600 | 26 | 58 | 0.198 | 30 |
| 5.5-0750 | 750 | 25 | 58 | 0.238 | 31 |
| 5.5-1000 | 1,000 | 20 | 58 | 0.254 | 32 |
| 5.5-1500 | 1,500 | 19 | 60 | 0.350 | 34 |
| 7.0-2000 | 2,000 | 40 | 64 | 0.920 | 60 |
| 7.0-4000 | 4,000 | 36 | 68 | 1.559 | 130 |

*These numbers assume a specific gravity of 1.0 and must be multiplied by the fluid specific gravity if it differs from 1.0.

## Table 4
## Motor Data Used in Practical Examples

| TYPE | HORSEPOWER | NAMEPLATE VOLTAGE | NAMEPLATE AMPERAGE | FULL LOAD EFFICIENCY (%) | FULL LOAD POWER FACTOR | COST ($) |
|---|---|---|---|---|---|---|
| 5.5 | 50 | 1,200 | 26 | 84 | 0.82 | 14,000 |
| 5.5 | 70 | 1,150 | 38 | 84 | 0.82 | 17,000 |
| 5.5 | 80 | 1,300 | 39 | 84 | 0.82 | 19,000 |
| 5.5 | 130 | 1,700 | 40 | 84 | 0.82 | 32,000 |
| 5.5 | 130 | 2,200 | 31 | 84 | 0.82 | 32,000 |
| 7.0 | 85 | 1,300 | 41 | 85 | 0.82 | 14,000 |
| 7.0 | 100 | 700 | 88 | 85 | 0.82 | 16,000 |
| 7.0 | 100 | 850 | 73 | 85 | 0.82 | 16,000 |
| 7.0 | 100 | 1,100 | 56 | 85 | 0.82 | 16,000 |
| 7.0 | 100 | 1,700 | 36 | 85 | 0.82 | 16,000 |
| 7.0 | 120 | 2,200 | 34 | 85 | 0.82 | 18,500 |

Table 5
Typical Tubing and Cable Prices Used in Practical Examples

| TUBING SIZE | COST PER FT |
|---|---|
| 2.375-in., 4.70-lbm/ft | $3.20 |
| 2.875-in., 6.50-lbm/ft | $4.00 |
| 3.500-in., 9.30-lbm/ft | $5.50 |

| CABLE SIZE | COST PER FT |
|---|---|
| 1 | $5.00 |
| 2 | $4.40 |
| 4 | $3.00 |
| 6 | $2.40 |

Table 6
Summary of Results of Practical Examples

| | ECONOMIC OPTIMUM | | | # COMMON PRACTICE | | | | |
|---|---|---|---|---|---|---|---|---|
| CASE NUMBER | TUBING SIZE (IN.) | CABLE SIZE | $U_T$ (kW) | TUBING SIZE (IN.) | CABLE SIZE | $U_T$ (kW) | ¢PAYOUT (YEARS) | *REF. 1 CABLE SIZE |
| 1 | 3.500 | 4 | 81.6222 | 3.500 | 6 | 82.7574 | 2.41 | 8 |
| 2 | 2.875 | 4 | 87.8751 | 2.375 | 6 | 95.9305 | 1.49 | 4 |
| 3 | 2.375 | 4 | 101.5222 | 2.375 | 6 | 106.9514 | 2.02 | 1 |
| 4 | 2.875 | 1 | 92.2510 | 2.375 | 2 | 100.4746 | 1.45 | 2/0 |
| 5 | 2.375 | 4 | 65.8538 | 2.375 | 6 | 69.7266 | 2.30 | 1/0 |
| 6 | 2.375 | 4 | 126.0527 | 2.375 | 6 | 130.6709 | 1.93 | 4 |
| 7 | 2.375 | @ 2 | 76.4487 | 2.375 | @ 2 | 76.4487 | -- | 2/0 |

# Head loss less than 100 ft per 1,000 ft and voltage loss less than 30 V per 1,000 ft.

* Reference 1 limits voltage drop to 5% of motor nameplate and addresses tubing size only in regard to casing clearance.

@ Governed by motor starting criteria.

¢ Economic optimum compared to common practice assuming a power cost of $0.05 per kW-hr.

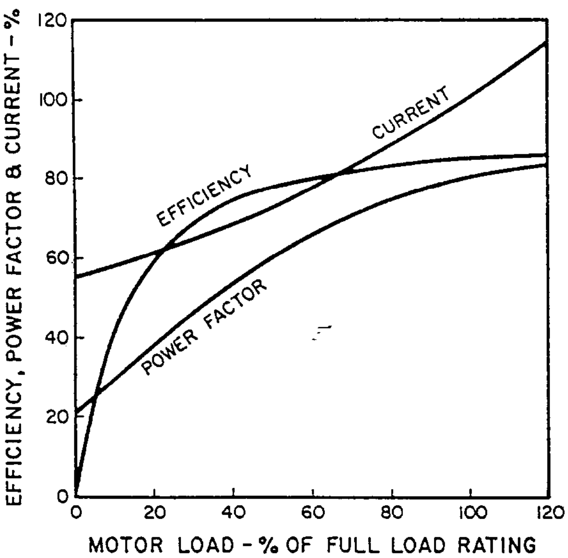


Figure 1 - Typical motor characteristics

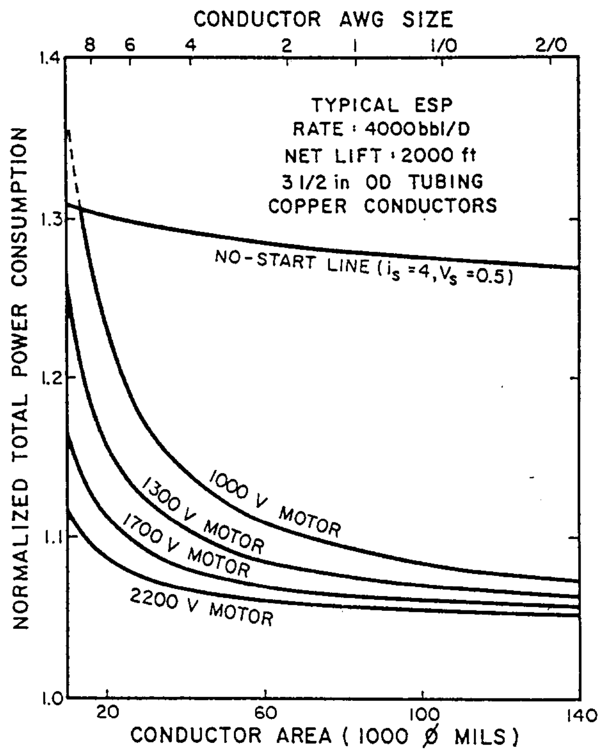


Figure 2 - Effect of motor voltage: high rate/shallow depth

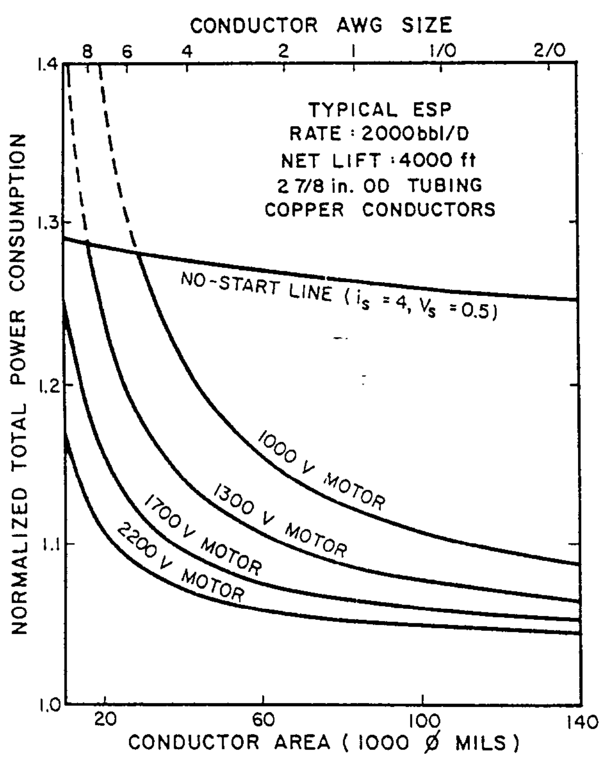


Figure 3 - Effect of motor voltage: medium rate/medium depth

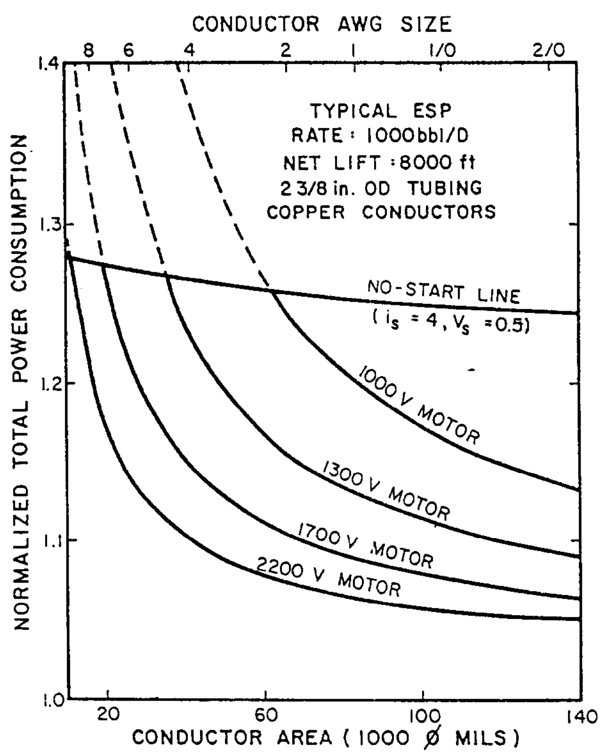


Figure 4 - Effect of motor voltage: low rate/great depth

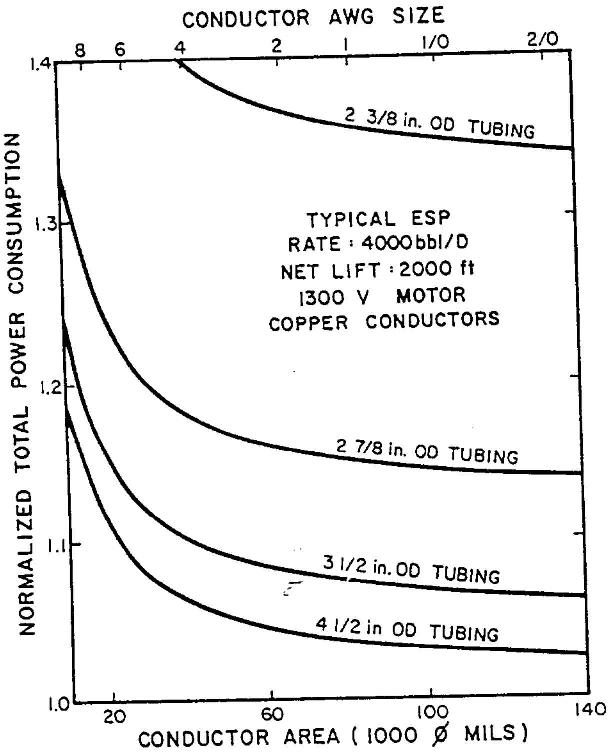


Figure 5 - Effect of tubing size: high rate/shallow depth

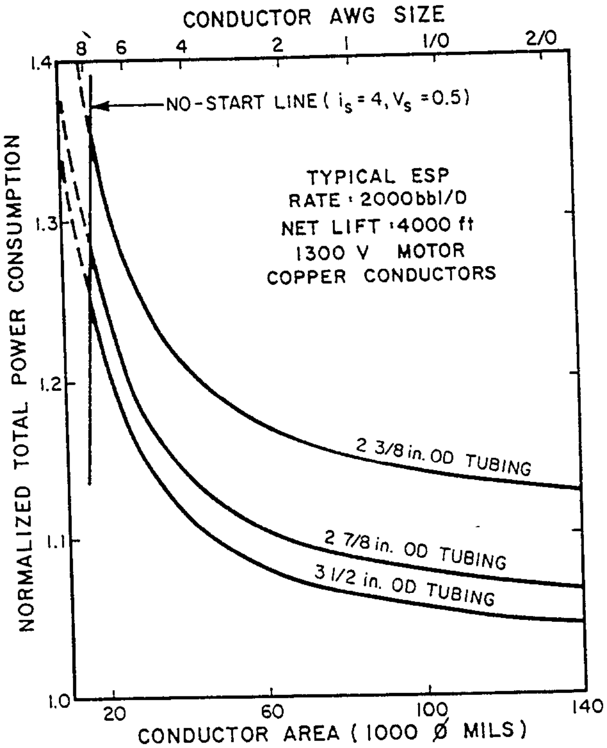


Figure 6 - Effect of tubing size: medium rate/medium depth

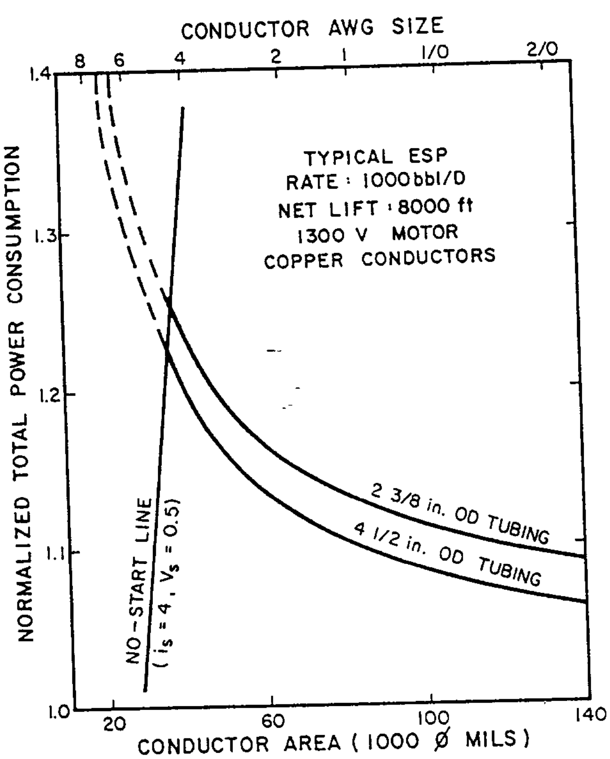


Figure 7 - Effect of tubing size: low rate/great depth

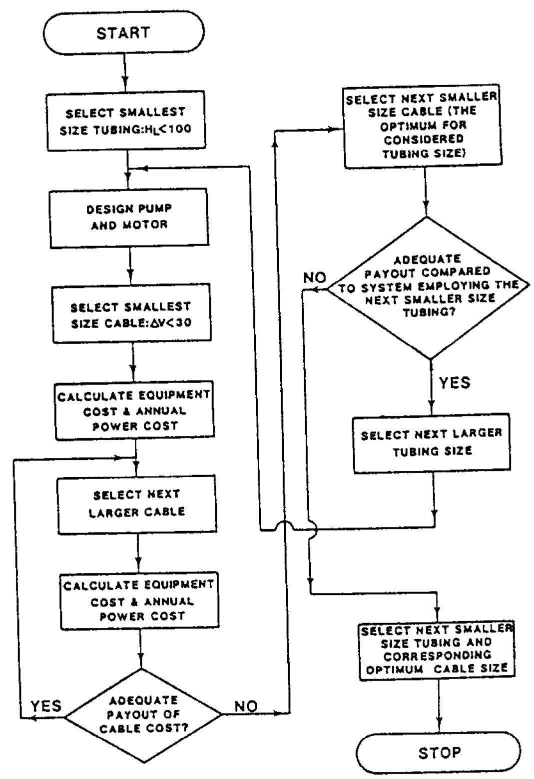


Figure 8 - Design procedure flow chart