Electrical Submersible Pumping (ESP) Systems

By

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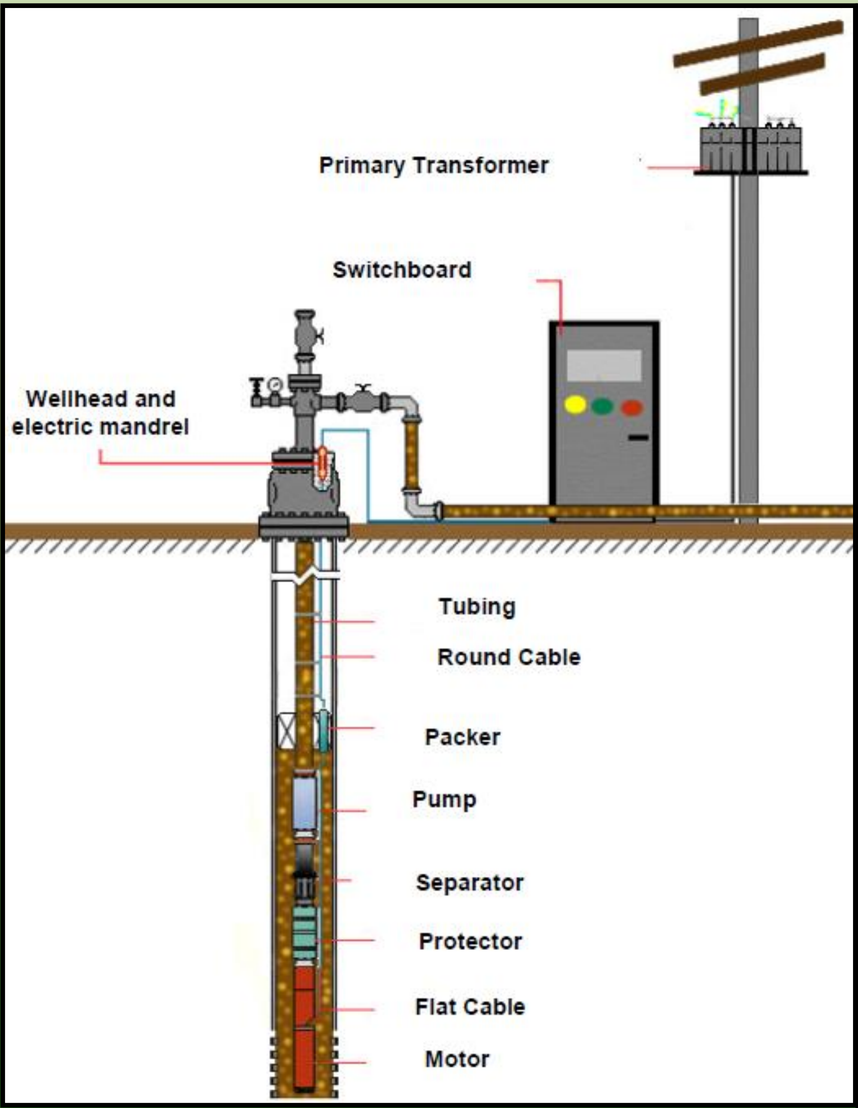
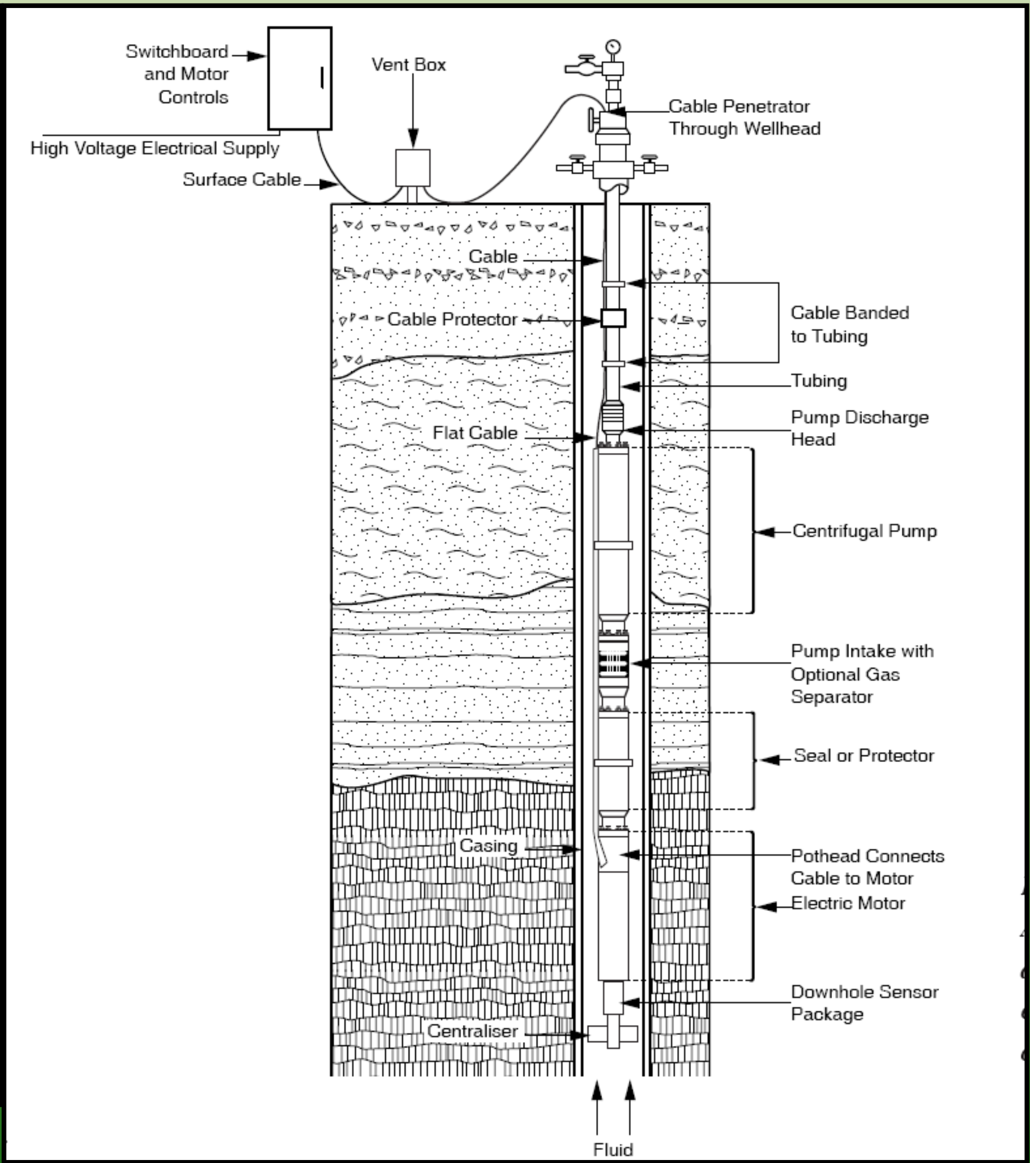
Lecture Outline

- Components and Operating Mechanism
  - Downhole Equipment
  - Surface Equipment
  - Gas Separators
- Installation Design
- Class Examples
- Operational Notes
- Summary

Overview of ESP





ESP Service Providers

- Schlumberger-REDA
- Centrilift – Baker Hughes
- Weatherford
- Wood Group ESP
- ALNAS (Russia)

ESP SYSTEM

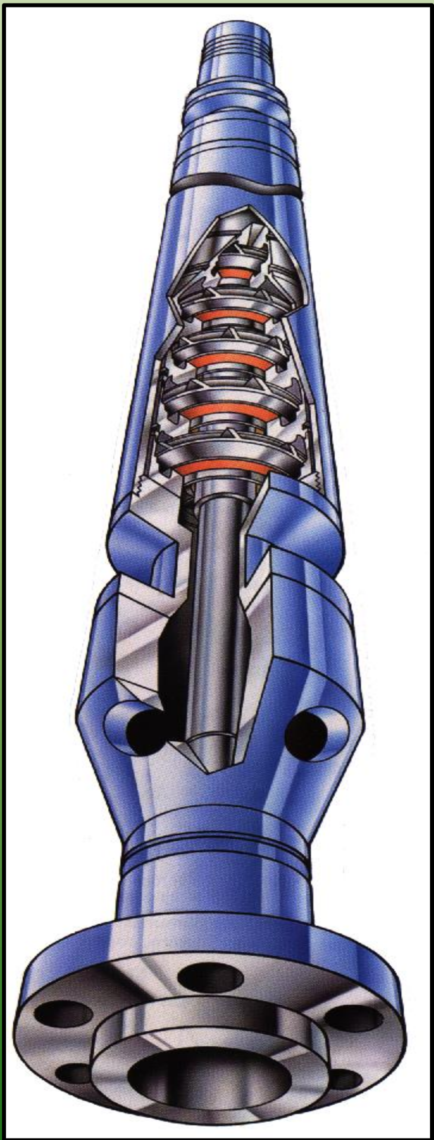
ESP system can be divided into surface components and downhole components. These components are listed below;

Surface Components:

- **Transformers**
- **Motor controller Switchboard of Variable Speed Drive (VSD) or Soft Start**
- **Junction Box**
- **Cable Venting box**
- **Wellhead**

Downhole Components:

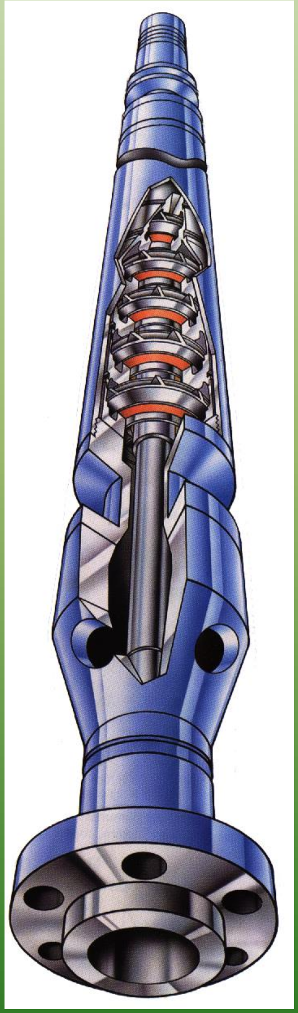
- **Cable**
- **Cable Guard**
- **Cable Clamps**
- **Pumps**
- **Gas Separator**
- **Seal Section**
- **Motor**
- **Sensor- Data Acquisition Instrumentation**
- **Drain Valve**
- **Check Valve**

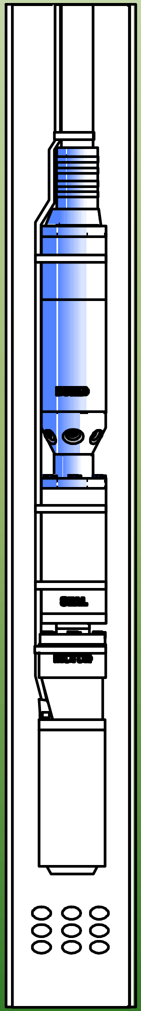


Downhole Centrifugal Pump

- Centrifugal pump is so named because the head added to fluid is due largely to centrifugal effects

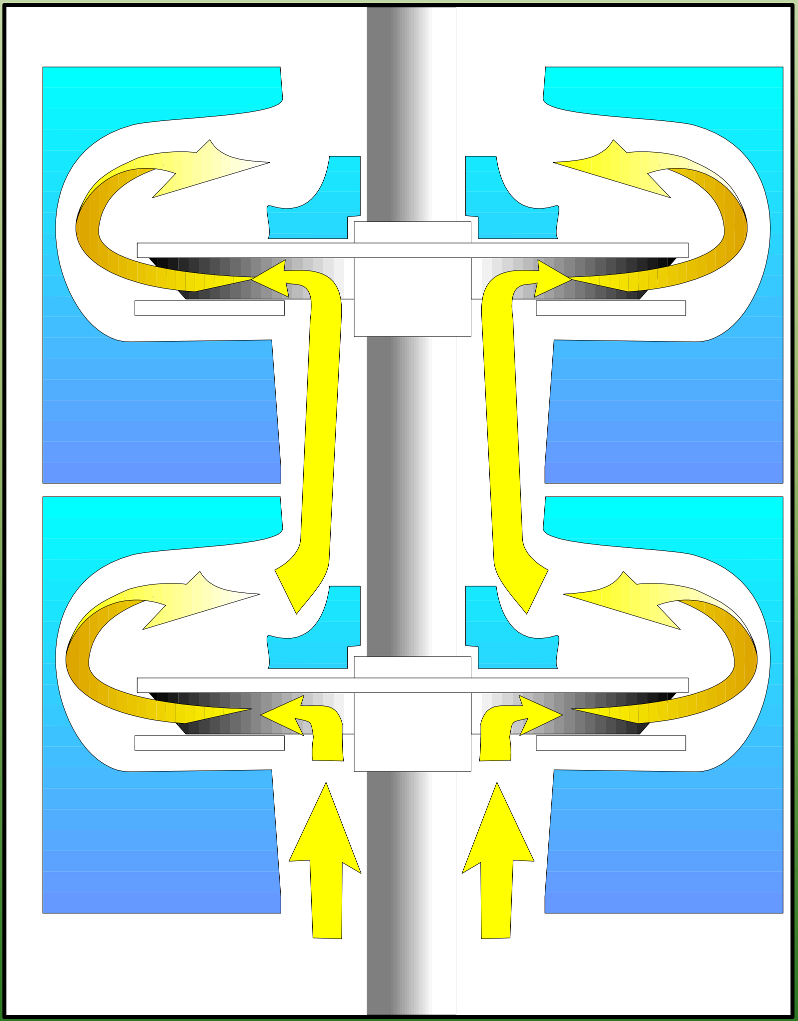
- Characterized by:
  - Small diameter
  - Large quantity of stages
  - High design loads





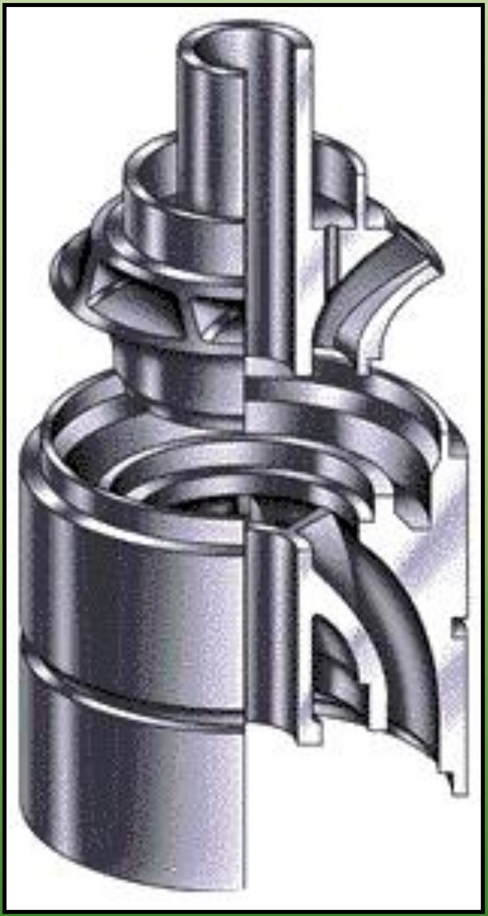
Pump Stage

- Fluid enters impeller through ‘eye’ near shaft and exits impeller on outer diameter (OD)
- Diffuser (in blue) redirects fluid into next impeller



Pump Impeller

Impeller in Diffuser = A Pump 'Stage'

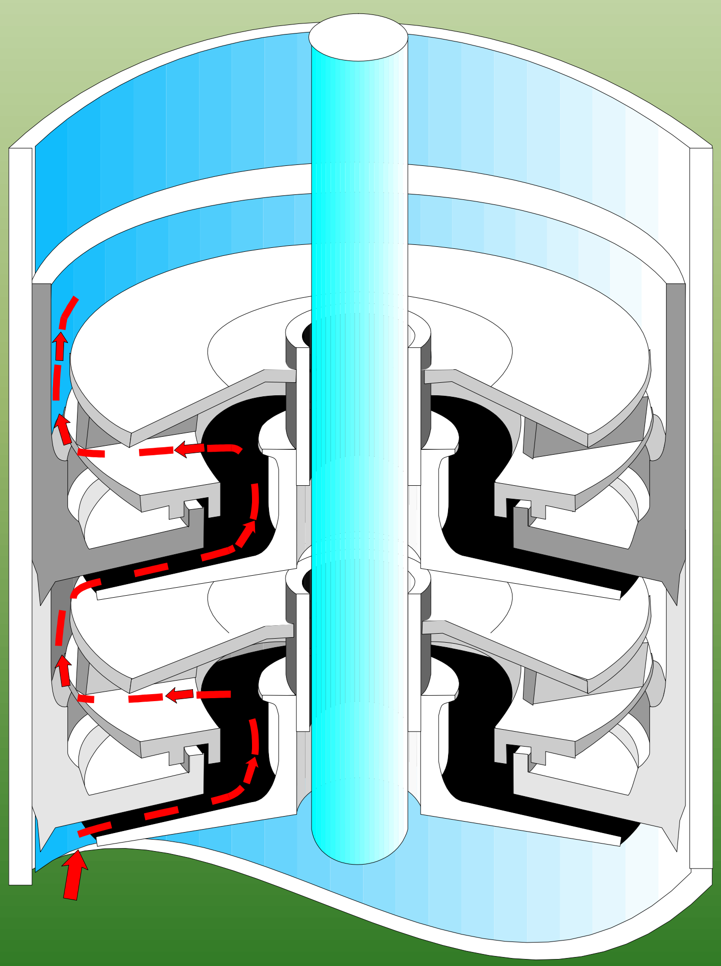


Mixed Flow Stage

Radial Flow Stage

Pump Stage

- Cut-away view of two impellers and diffusers
- By stacking impellers and diffusers (multi-staging), desired lift (TDH-Total Dynamic Head) is achieved

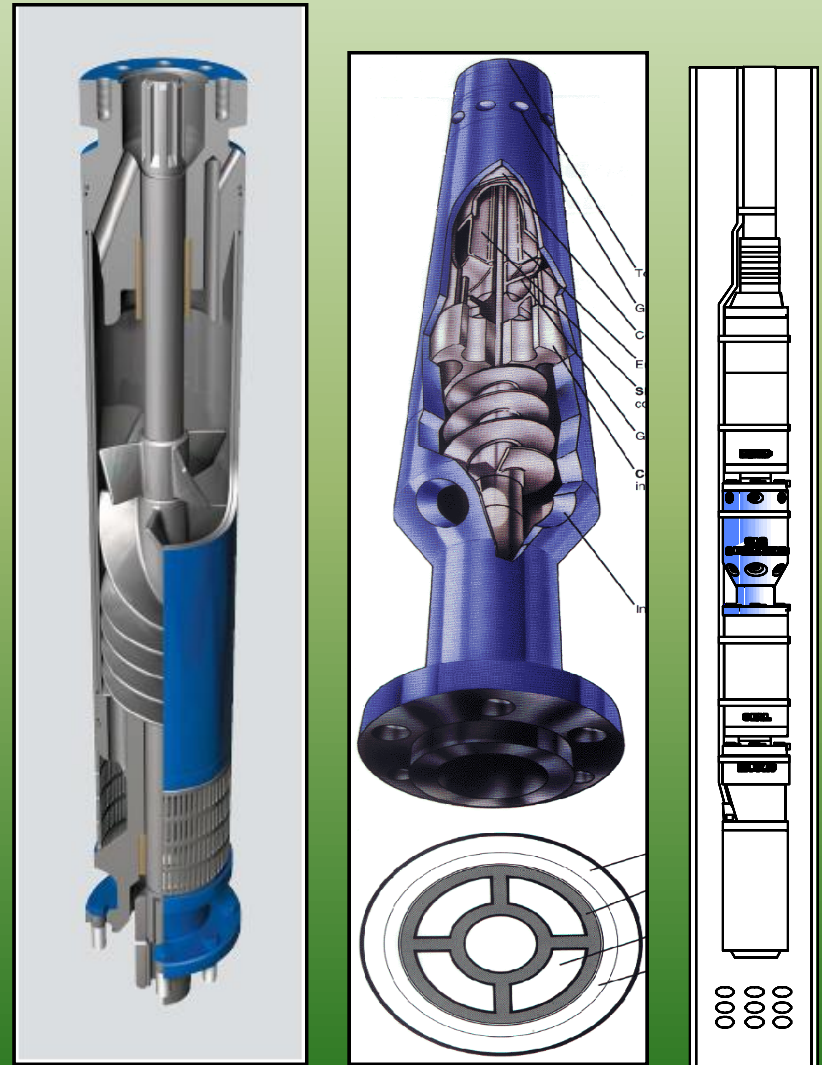


Gas Separators

- Used in applications where free gas causes interference with pump performance

- Units separate some of free gas from fluid stream entering pump to improve pump's performance

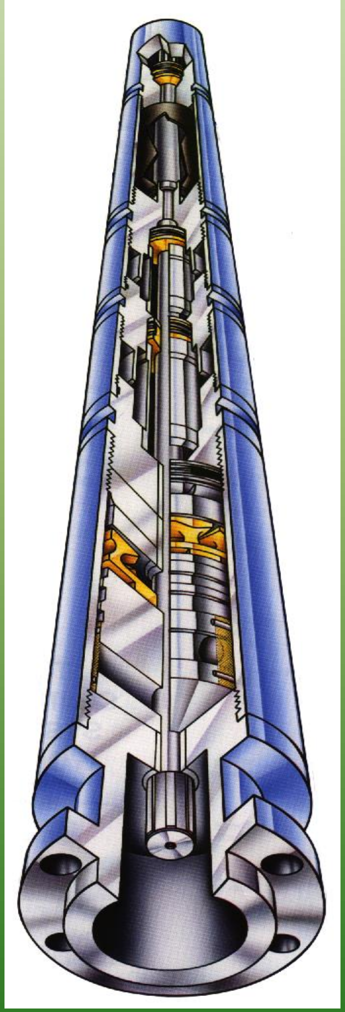
Homogenizer

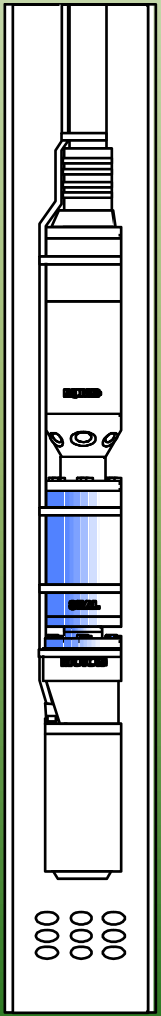


Separators

Seal Section

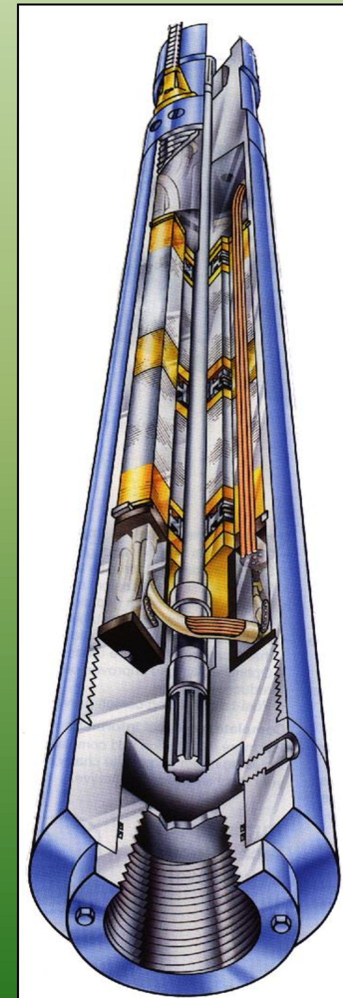
- Protects motor from contamination by well fluid
- Absorbs thrust from pump
- Equalizes pressure between wellbore and motor

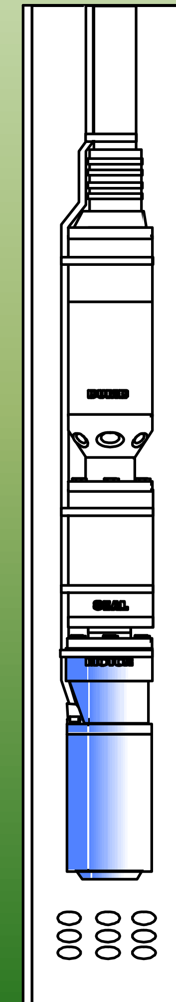




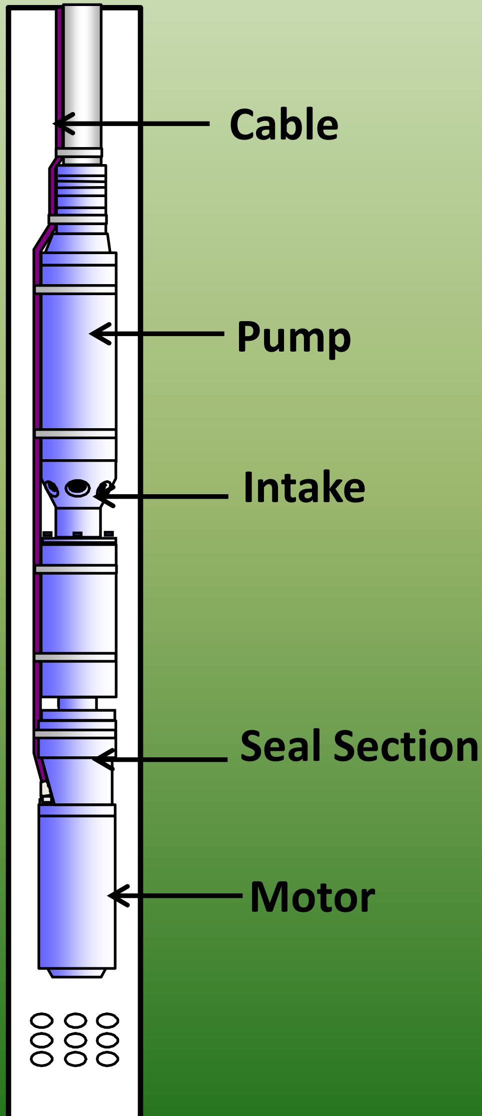
Submersible Motor

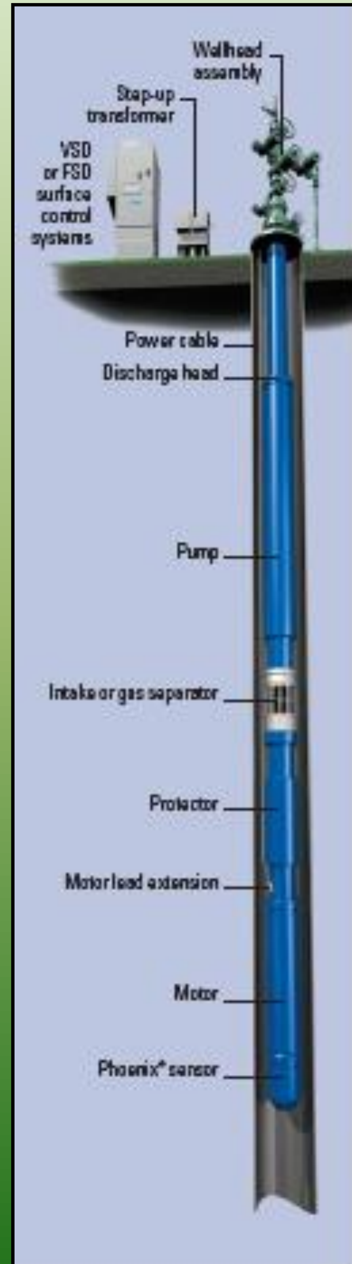
- Motor is filled with oil
- It is a two-pole, three phase, 3,600 rpm (revolutions per minute) design
- Motor components are designed to withstand up to 500^{o}F temperatures





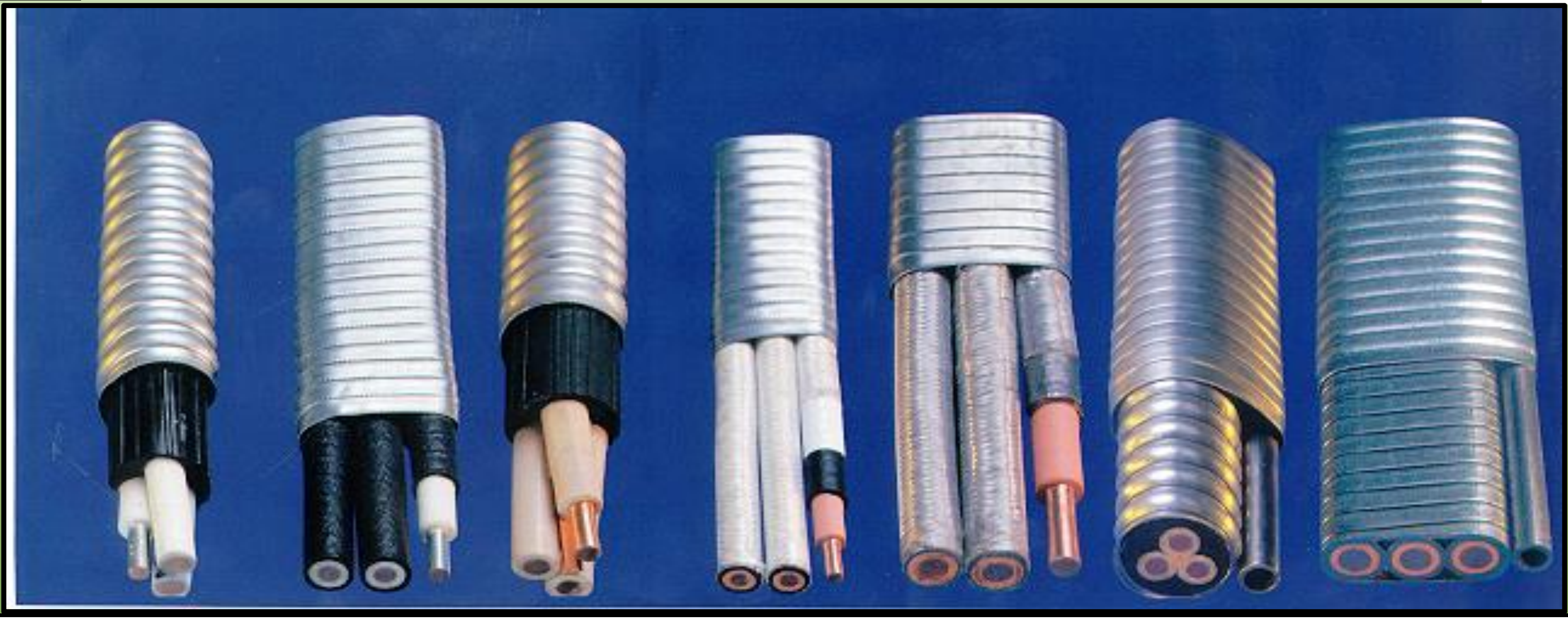
Downhole Components





Sensor can also be added to the pump below the motor to acquire data like downhole pressure, temperature, and vibration, these supply pump monitoring data.

Electric Power Cable



There are different types of cables available in the industry. These include;

- Round Cables
- Flat Cables
- Number of conductors also varies from 1,2,4 etc…depending on company

Cables also vary depending on the type of insulation based on the working environment, there are special cable insulation for corrosive fluids and severe environments.

Parts of a Pump's Electrical Cable

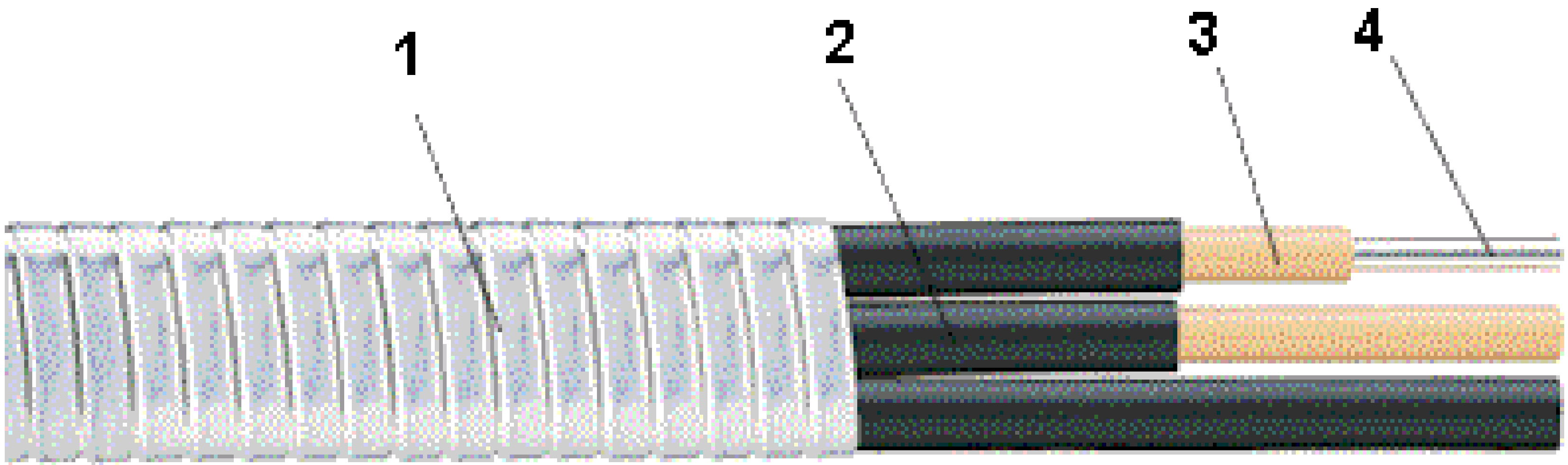
FLAT CABLE

1 - Armor: Galvanized Steel

2 - Jacket: Electrical Grade Thermoplastic Insulation

3 - Insulation: High Dielectric Thermoplastic Insulation

4 - Conductor: Soft Drawn Tin Coated Copper (SDTC)



CTT Flat

Surface Equipment: Transformer

The transformer is a device that transforms the voltage of an electrical system. For example a transformer that converts 7200 volts to 480 volts. This is accomplished by two sets of coils wrapped around an iron core in the transformer. In this case the transformation ratio is 7200/480. Transformers are rated in KVA capacity. This depends on the voltage and the current the transformer can handle.

KVA = KV * A

KV = Voltage in Kilovolts
A= Current in Amperes

Power and control Skids

Surface Equipment: Motor Controllers

Motor Controllers;

- **Fixed Speed Controller**
- **Variable Speed Controller**

EQUIPMENT SIZING AND DESIGN

ESP Design Considerations

ESP Design

- Wells with Low GOR and High Water Cut
- Wells with High GOR
- Wells Producing Viscous Fluids
- Variable Speed Design

Design Guidelines
Steps Based Design

STEP	Design Task	Description
1	Basic Data	Collect and analyze all well data to be used
2	Well Production Capacity	Determine the production capacity and depth
3	Fluid Volume Calculations	Calculate all fluid volumes at pump intake pressure
4	Total Dynamic Head (TDH)	Determine the pump's discharge requirements
5	Pump Type	Select pump that has highest efficiency based on desired flow rate
6	Optimum Size of Components	Select optimal size of pump, motor, seal section and check the limitations if any
7	Electric Cable	Select correct type and size of cable based on well
8	Accessory and Optional Equipment	Select motor controller, transformer, tubing head and other optional equipment
9	Variable Speed Pumping System	For additional operational flexibility, select the variable speed submersible pumping system

STEP 1: Basic Data

The first step in an ESP design is to collect and verify the reliability of all data that will be used in the design. The following is a listing of the data required.

Well Data: Casing size and weight, Tubing size, type and thread, Perforated or open hole, Pump setting depth (measured and vertical), Deviation survey

Production Data: Wellhead casing pressure, Wellhead tubing pressure, Present production rate, Production fluid level/Pump intake pressure, Static fluid level/ Static Bottom hole pressure, Datum point, Bottom-hole temperature, Desired production rate, Gas-oil ration, Water cut.

Well Fluid Conditions: Specific gravity of water, Oil API or specific gravity, Specific gravity of gas, Bubble-point pressure of gas, Viscosity of oil, PVT data.

Power Sources: Available primary voltage, Frequency, Power source capabilities

Possible Problems: Sand, Deposition, Corrosion, Paraffin, Emulsion, Gas, Temperature

STEP 2: Well Production Capacity

The Inflow Performance Relationship (IPR) or the Productivity Index (PI) of the well depending on the pressure regime should be integrated with the Vertical Lift Performance (VLP) Curve to determine the productive capacity of the well which would be used in the ESP design.

STEP 3: Fluid Volumes Calculation

The accurate calculation of fluid volumes and type at the pump intake is very important in pump design. The presence and volume of free gas at the pump intake must be taken into consideration. The presence of free gas may considerably decrease the required discharge pressure, hence there may be a need to use a gas separator at the pump intake to achieve maximum system efficiency. Ideally, if the gas remains in solution, the pump behaves normally, however as gas to liquid ratio increases beyond the critical value of between 10-15%, the pump efficiency decreases and lower pump head is produced.

Hence, the percent free gas must be calculated so that the right gas separator technique/device can be chosen and integrated in the ESP design.

STEP 3: Fluid Volumes Calculation-B

The free gas volume is calculate from the following equations/correlations, if PVT values are not available.

a. Solution Gas Oil Ratio (Dissolved Gas Oil Ratio)

Using Standing's correlation (any suitable correlation can be used);

$$\boldsymbol{R_s} = \gamma_g * \left[\frac{P_b}{18} * \frac{10^{0.0125*API}}{10^{0.00091*T}}\right]^{1.20482}$$

Where,

γ_g= Specific gas gravity

P_b= Bubble Point pressure (psi)

T = Bottom-hole Temperature ^{O}F

b. **Gas Volume Factor**

$$B_g = 5.04\frac{zT}{p}$$

Z=Gas compressibility factor

T= Bottom hole temperature, ^{O}R

P= Pressure, psi

B_g= Gas volume factor, bbls/STD

STEP 3: Fluid Volumes Calculation-C

C. Oil Formation Volume Factor, Bo

$$B_o = 0.972 + 0.000147 * \left[R_s * \left(\frac{\gamma_g}{\gamma_o}\right)^{0.5} + 1.25 * T\right]^{1.175}$$

Where,

B_o= Oil formation Volume Factor

R_s= Solution Gas Oil Ration (SCF/STB)

γ_g= Gas Specific gravity (Relative to Air)

γ_o= Oil Specific Gravity (Relative to water)

d. Total Volume of Fluids

$$Total\ Gas = \frac{Producing\ GOR * BOPD}{1000} = MCF$$

$$Solution\ Gas = \frac{R_s * BOPD}{1000} = MCF$$

$$Freegas = Total\ Gas\ - Solution\ gas$$

STEP 3: Fluid Volumes Calculation-D

$$Volume\ of\ Oil\ @\ Pump\ Intake, \qquad V_o = BOPD * B_o$$

$$Volume\ of\ gas\ @\ the\ Pump\ Intake, \qquad V_g = Free\ gas\ * B_g$$

$$Volume\ of\ water\ @\ Pump\ Intake, \qquad V_w = BWPD * B_w$$

$$Total\ Fluid\ Volume, \qquad V_T = V_g + V_o + V_w$$

$$Percentage\ of\ free\ gas\ to\ total\ volumme,$$

$$\%\ Free\ gas = \frac{V_g}{V_T}$$

This is the amount of gas at the pump intake, the critical % is between 10-15 %, above, a solution to the gas volume must be included in the design (gas separator)

STEP 4: Total Dynamic Head (TDH)

Next, the total dynamic head (TDH) required to pump the desired capacity is determined. The total dynamic head is the height in feet of fluid being pumped.

$$TDH = Net\ well\ lift\ (dynamic\ lift) + Tubing\ Friction\ Loss + Wellhead\ Discharge$$

$$TDH = H_d + F_t + P_d$$

Where,

H_d = *Vertical Distance in feet between the wellhead and estimated producing fluid level at the expected capacity*

$F_t = The\ head\ required\ to\ overcome\ friction\ loss\ in\ the\ tubing\ measured\ in\ ft$

$P_d = The\ head\ required\ to\ overcome\ friction\ in\ the\ surface\ pipe, valves\ and\ fittings\ and\ to\ overcome\ elevation\ changes\ between\ wellhead\ and\ tank\ battery.$ $It\ is\ converted\ from\ pressure\ to\ head$

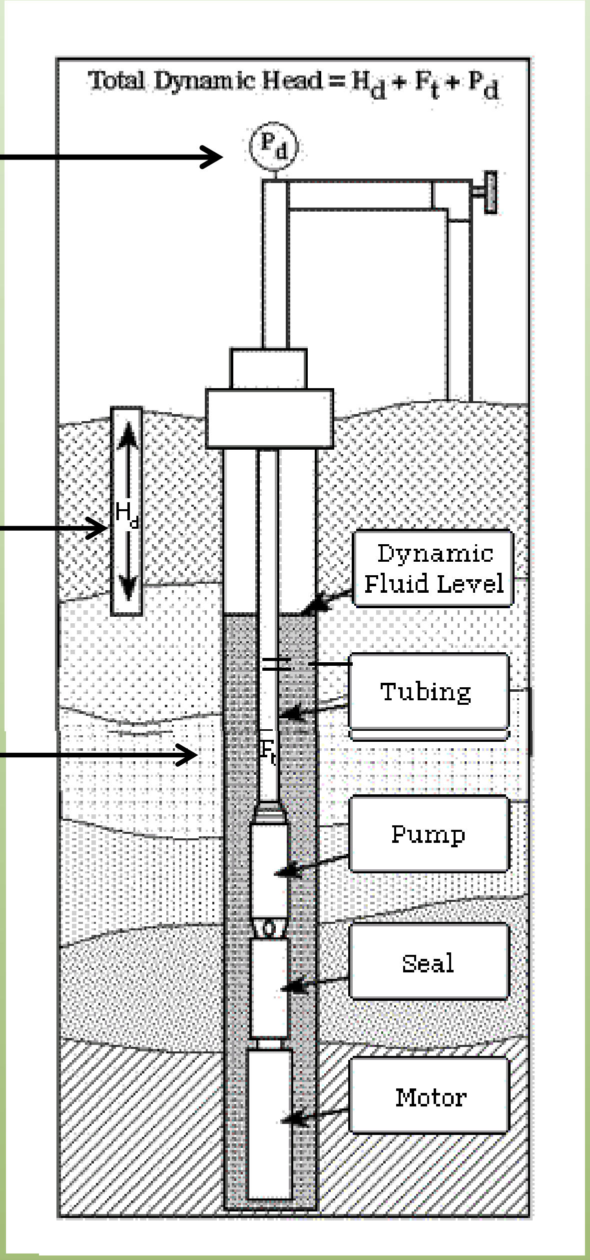
$$P_d = \frac{psi * 2.31\ ft/psi}{specific\ gravity} \quad or \quad P_d = \frac{psi}{0.433 \frac{psi}{ft} * specific\ gravity}$$

P_d

H_d

F_t

$$TDH = H_d + F_t + P_d$$



Total Dynamic Head

STEP 5: Pump Type Selection-A

Once the TDH has been calculated, its time to select a Pump. The pump type is selected from the **ESP Catalogue of the Service Company** you are interested in buying the pump from. ESP providers have tables that gives engineering information about pumps and also Pump Performance Curves that shows how pump performs at given conditions when tested with water.

Tabulated Engineering data on pumps include (**this may vary with companies**);

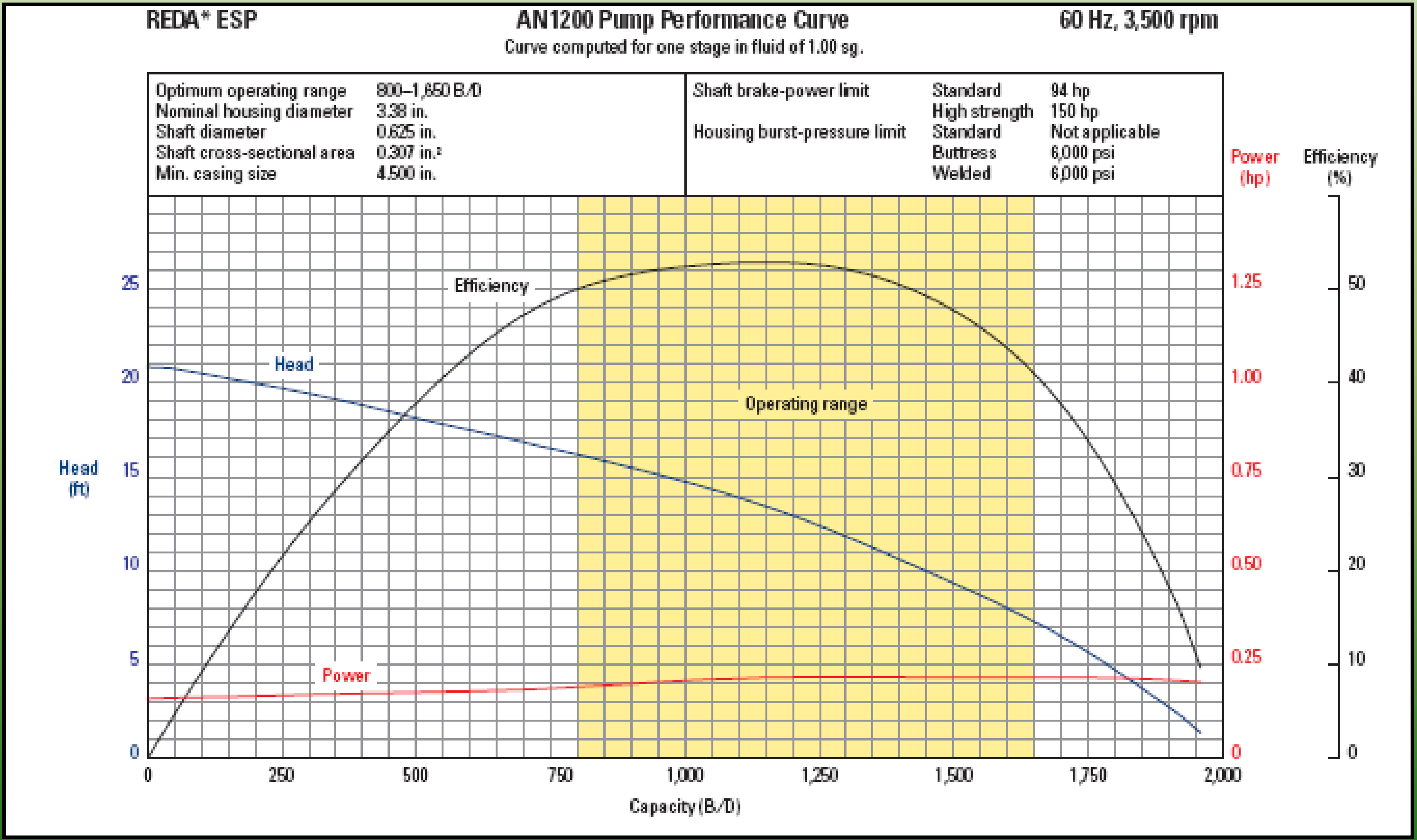
- Suitable Casing Size for Pump
- Weight of Casing
- Stage Type (Radial or Mixed)
- Best Efficiency Producing (BEP) rate
- Motor, Seal Section and Pump
- Operating Range (60 Hz or 50 Hz) depending on local voltage

The Pump Performance Curve is a plot of production volume per stage against;

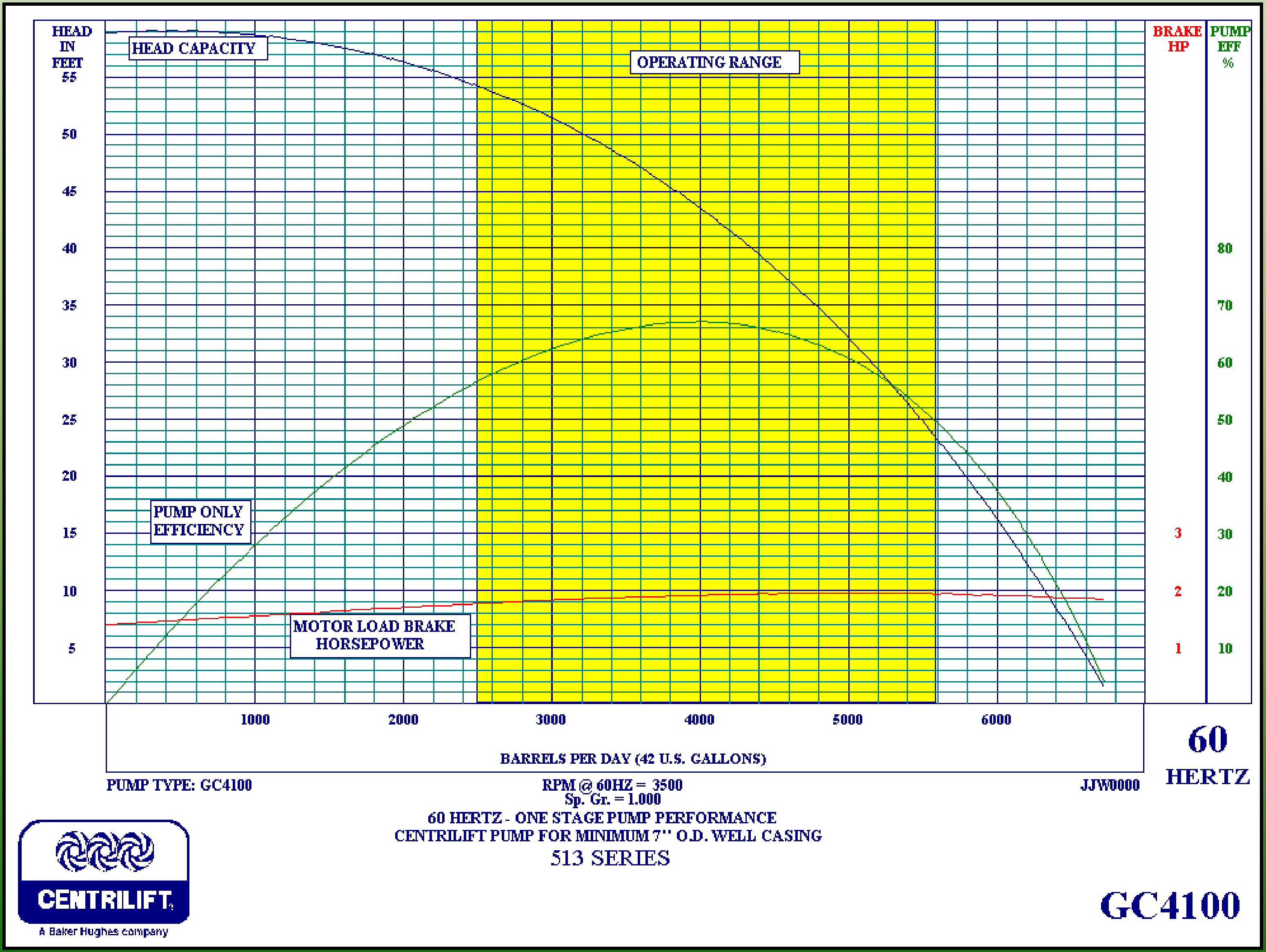
- Pump Head
- Break Horsepower
- Efficiency

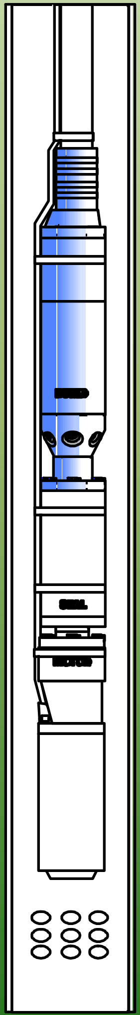
It also shows the recommended operating range

An Example Pump Performance Curve REDA ESP (Schlumberger)



Typical Pump Performance Curve Centrilift (Baker Hughes)





STEP 5: Pump Type Selection-B

Notes on Pump Selection:

- Larger diameter pumps and motor are less expensive and they operate at higher efficiencies.
- Select the highest efficient pump that will fit in the casing
- If the well's production capacity is not accurately known, choose a pump with a steep characteristic curve.
- If desired volume falls at a point where two pumps have approximately the same efficiency, choose the pump type which requires the greater number of stages.
- If gas is present in the produced fluid, a gas separator may be required to achieve efficient operation.
- In wells with viscous fluids or emulsions, some pump corrections may be necessary to ensure more efficient operation, hence, working with a service company personnel will be expedient.

STEP 5: Pump Type Selection-C

Notes on Pump Selection:

In most cases there will be two or three pumps that meet the volume and diameter requirements. A comparison of efficiencies, expected production changes and actual pump efficiencies are used to select the optimum pump.

Other considerations are;

- Availability of pump in customer inventory
- Delivery Equipment

STEP 6: Optimum Size of Components-A

ESP components are usually designed and build in a number of different sizes, hence the components can be assembled in a variety of combinations. These combinations must be carefully determined to operate the pump at the optimal production rate, material strength and temperature limits based on the Company's catalogue.

Engineering considerations for sizing pump's components include;

- Maximum Loading Limits
- Maximum Diameter of Unit
- Velocity of fluid passing a motor (this affects rate of pump cooling, a velocity of 1 ft/s is recommended, if not achievable a motor jacket may be required to increase the velocity).
- Shaft horse power (HP) limitations at various frequencies

STEP 6: Optimum Size of Components-B

a. Optimum Selection of Pump

From the Performance Curve of the selected pump type, determine the number of stages required to produce the anticipated capacity based on the calculated dynamic head (TDH). Note that the performance curves are **single stage** pump characteristic curves, hence the total stages required is determined from;

$$Total\ Stages\ Required = \frac{Total\ Dynamic\ Head}{Head\ per\ stage}$$

b. Housing Pressure Limit

Maximum housing pressure will occur at pump shut in, when the maximum lift per stage is available. Worst case is when the pump is pumping against a closed valve.

$$MHP = SIH_{60} * Stages * Mixture\ gradient * (Hz/60)^2$$

$\boldsymbol{MHP}$: Maximum Housing Pressure

SIH: Shut-in head per stage @ 60Hz.

Stages: Number of pump stages

Hz: Operating Frequency

STEP 6: Optimum Size of Components-C

C. Optimum Selection of Motor

The optimum motor is selected by first determining the brake horsepower required per stage by the pump. This value is also gotten from performance curve. Therefore, brake horsepower (BHP) required to drive a pump is then calculated from;

$$BHP = Total\ Stages * BHP\ per\ stage * Specific\ gravity$$

STEP 6: Optimum Size of Components-C

d. Optimum Selection of the Seal Section

Refer to company catalogue for recommendations based on pump type and well environment.

e. Optimum Selection of Gas Separator

Refer to company catalogue for recommendations based on pump type and well environment. Make the necessary adjustments in horsepower requirements and housing length.

Note: More power will be needed by the motor to drive an added gas separator, this must be added on when selecting the motor, if a gas separator would be needed in the pump.

STEP 7: Electrical Cable-A

Electric cable to be used is selected based on the evaluation of the following parameters:

Cable Size

Cable size is dependent on voltage drop, amperage and available space between casing and collars. Company catalogues have to be consulted for these values. However, its is recommended that the voltage drop should be less than 30 volts/1000 ft or less than 15% of motor nameplate voltage. This is to ensure that adequate voltage is available to operate the motor downhole.

Cable Type

This is based primarily on the fluid conditions, bottom-hole temperature and annular space limitations. Use flat cable for limited space installations.

STEP 7: Electrical Cable-B

Cable Length

Total cable length should be at least 100ft more than the measured pump setting depth in order to have sufficient lengths for surface connections. Make surface connections a safe distance from the well head.

Cable Venting

As a safety precaution, it is necessary to vent gas from the cable prior to the motor controller to avoid explosive conditions. A cable venting box should be used for this purpose.

Example Electrical Cable Specification-A

Oil Well Cable

Model	MaxT deg.F	Min T deg.F	Flat Round	Insulation	Jacket	Application
CTT	190	-40	F	Thermo-plastic	Thermo-plastic	Shallow wells, Water wells, Low CO_2 Light ends
CPN	205	-30	F/R	Poly-propylene	Nitrile	General
CPL	225	-40	F	Poly-propylene	Lead	Gassy Wells, High CO_2 H2S
CEN	280	-30	F/R	EPDM w/Tape	Nitrile	Low to Moderate Gassy Conditions
CEE	400	-60	F/R	EPDM	EPDM w/ Tape, Braid	Moderate Gassy
CEB	300 or 400		R	EPDM W/ Extruded Fluro-polymer	EPDM	Gassy Wells
CEL	450	-40	F/R	EPDM	Lead w/ Bedding Tape	Hot Gassy Wells

Example Electrical Cable Specification-B

Centriline CTT Flat -40°F (-40°C) to 190°F (88°C)
Specifications

Part No.	KV Rating	Cond Size	Conductor Diameter		Insulation Diameter		Jacket Diameter		Overall Dimension		Weight Per	
			Inch	mm	Inch	mm	Inch	mm	Inch	mm	Lb/Ft	Kg/M
76574	3	6-1	0.162	4.11	0.288	7.32	0.394	10.01	0.514 x 1.272	13.06 x 32.31	0.71	1.06
76560	3	4-1	0.204	5.18	0.330	8.38	0.436	11.07	0.556 x 1.398	14.12 x 35.51	0.90	1.34
76572	3	2-1	0.258	6.55	0.384	9.75	0.490	12.45	0.610 x 1.560	15.49 x 39.62	1.20	1.79
76573	3	1-1	0.289	7.34	0.415	10.54	0.521	13.23	0.641 x 1.654	16.28 x 42.01	1.39	2.06

- 1 inch = 25.40 millimeters
- 1 pound per foot = 1.488 kilograms per meter
- All finished dimensions are nominal, + 0.040" tolerance.
- Weight is + 8% tolerance.
- Materials and specifications are subject to change without notice.
- Stranded conductors will be supplied on request.
- Flat cable construction has 0.020" thickness, galvanized steel armor.

STEP 8: Accessories and Other Equipment

a. **Downhole Accessories**
Cable Bands, Cable guard
Swaged nipple
Check Valve
Drain Valve

b. **Motor Controllers**

c. **Transformers**
The type of transformer selected depends on the size of the primary power system and the required secondary voltage.

d. **Wellhead and Accessories**
Select wellhead on the basis of casing size, tubing size, maximum recommended load, surface pressure and maximum setting depth.

e. Surface Cable

f. **Service Equipment** like cable reels, shipping cases etc.

g. **Optional Equipment**

- Bottom-hole pressure sensing device- For continuous measurement of bottom hole pressure
- Automatic Well Monitoring - This can be used for remote monitoring of wells.

STEP 9: Variable Speed Submersible Pumping (VSSP)

The ESP system can be modified to include an Electrospeed variable frequency controller so that it operates over a much broader range of capacity, head and efficiency. The speed of an ESP motor is proportional to its frequency of the electrical power supply. Thus by adjusting the frequency, the speed can be adjusted, this is the purpose of the variable speed system.

This system offers potential for boosting production, reducing downtime, and increasing profit. Also it can be used to extend the range of a submersible pump.

Also, if the production capacity of a well is not precisely known an variable speed controller can be selected for an estimated range of and adjusted for the desired production level once more data is available.

Design Class Examples

Question 1

Given the following data:
Lift required: 6200 ft
Rate: 2300 bpd
Fluid SG: 1.0
Operating Frequency: 60 Hz

Find:

a) The number of Stages required
b) The minimum motor horsepower required
c) The pump efficiency

Question 2

Given the following data:
Pump Depth: 7500 ft
Tubing Pressure: 150 psig
Pump Intake Pressure (PIP): 275 psig
Rate: 3000 bpd
Mixture Gradient: 0.42 psi/ft
Tubing : 2 7/8 in. OD (New)

Calculate:

a. The Total Dynamic Head (TDH)

Question 3

Given:
Casing: 7in., 26 lb/ft
TDH: 7427 ft
Casing Drift Diameter: 6.151 in.
Rate: 2500 bpd
Operating Frequency: 60 Hz

Find the largest diameter pump that will fit in the casing.

Design Example 4

Question: Select a suitable Submersible Pumping System for the following well and production data.

Well Data
Casing: 7in. OD., 23 lbs/ft
Tubing: 2 7/8 in. OD., External Upset 8 Round Thread (new)
Perforations: 5300-5400 ft
Pump Setting Depth: 5200 ft (measured and vertical)

Production Data
Wellhead Tubing Pressure: 150 psi
Test Rate: 900 bpd
Datum Point: 5350 ft
Test Pressure: 985 psi
Static bottom Hole Pressure: 1650 psi
Bottom-hole Temperature: 180 ^{O}F
Gas oil Ratio- Not Available
Water Cut: 90%
Desired Production Rate: 2000 bpd (stock Tank)

Well Fluid Conditions
Water SG: 1.02
Oil API: 30^{O} (0.876)
Gas SG: Not Available
Bubble Point Pressure : Not Available
Viscosity of Oil: Not Available

Power Sources
Available Primary Voltage:7200/12470 volts
Frequency: 60 Hz
Power Source Capability: Stable System

Possible Problems
None

Design Example 5

Question: Select a suitable Submersible Pumping System for the following well and production data.

Well Data
Casing: 5 ½ in. OD., 17 lbs/ft
Tubing: 2 3/8 in. OD., External Upset 8 Round Thread (new)
Perforations: 5500-6000 ft
Pump Setting Depth: 5000 ft (measured and vertical)

Production Data
Desired Production: 1000 bpd (Stock Tank)
Pump Intake Pressure @ 1000 bpd: 850 psi
Water Cut: 65%
Wellhead Pressure: 120 psi
Producing GOR: 430 scf/stb
Bottom-hole Temperature: 165 ^{O}F

Well Fluid Conditions
Water SG: 1.08
Oil API: 35^{O} (0.85)
Gas SG: 0.65
Bubble Point Pressure : 2000 psi
Viscosity of Oil: Not Available

Power Sources
Available Primary Voltage:7200/12470 volts
Frequency: 60 Hz
Power Source Capability: Stable System

Possible Problems
Gas

Design Example 6

Select the right pump for the data given below:

Casing: 7 in., 26 lb/fts
Tubing: 2 3/8 4.7 #/ft (ID=1.996 in.)
SG_O= 0.865 (32^O API)
SG_W= 1.04
SG_g= 0.8
$Q_{O\ SC}$= 150 STB/D
$Q_{g\ \ SC}$= 450 STB/D
GOR: 225 SCF/STB
Bubble Point Pressure: 550 psi
BHT: 145 ^{O}F
Tubing Pressure: 100 psi
Casing Pressure: 100 psi
Top Perforation: 6000 ft
Pump depth: 5500 ft

Summary

- ESP system have been introduced and the operational mechanism explained in details.
- The design methodology, equations and steps were presented.
- Design examples were also shown and demonstrated in class.

References

- WG Wood Group "Basic ESP Sizing Manual", 2007
- Baker Hughes, Centrilift, "Handbook for Electrical Submersible Pumping System", 1997.
- Schlumberger REDA Electric Submersible Pump Technology, ESP Catalogue, 2006

Electrical Submersible Pump Systems

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