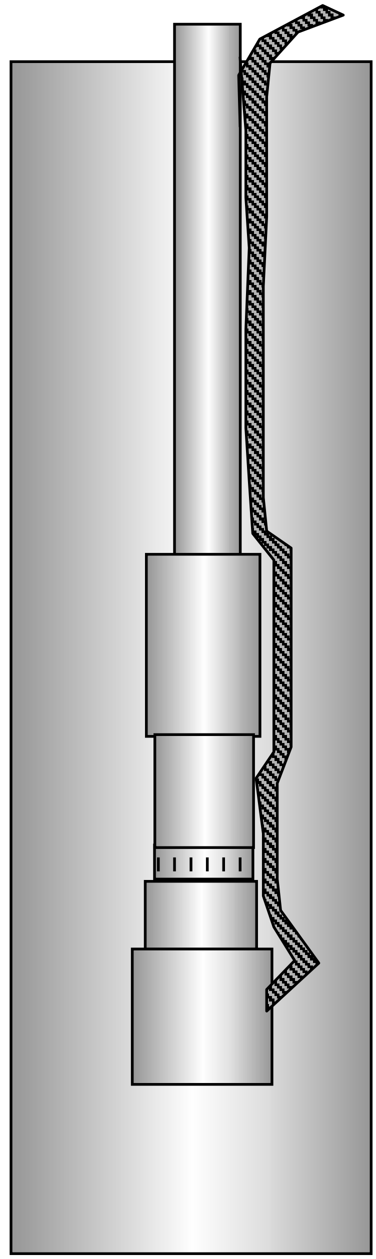
Electric Submersible Pump Basics



Burney Waring
SIEP
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Contents

1 Introduction

We will discuss the basics of ESPs by looking at their function, their parts, and their operation. This discussion will cover the following topics:

Inflow & Outflow

The ESP system

Pump

Pump Intake

Motor

Equalizer

Cable

VSD

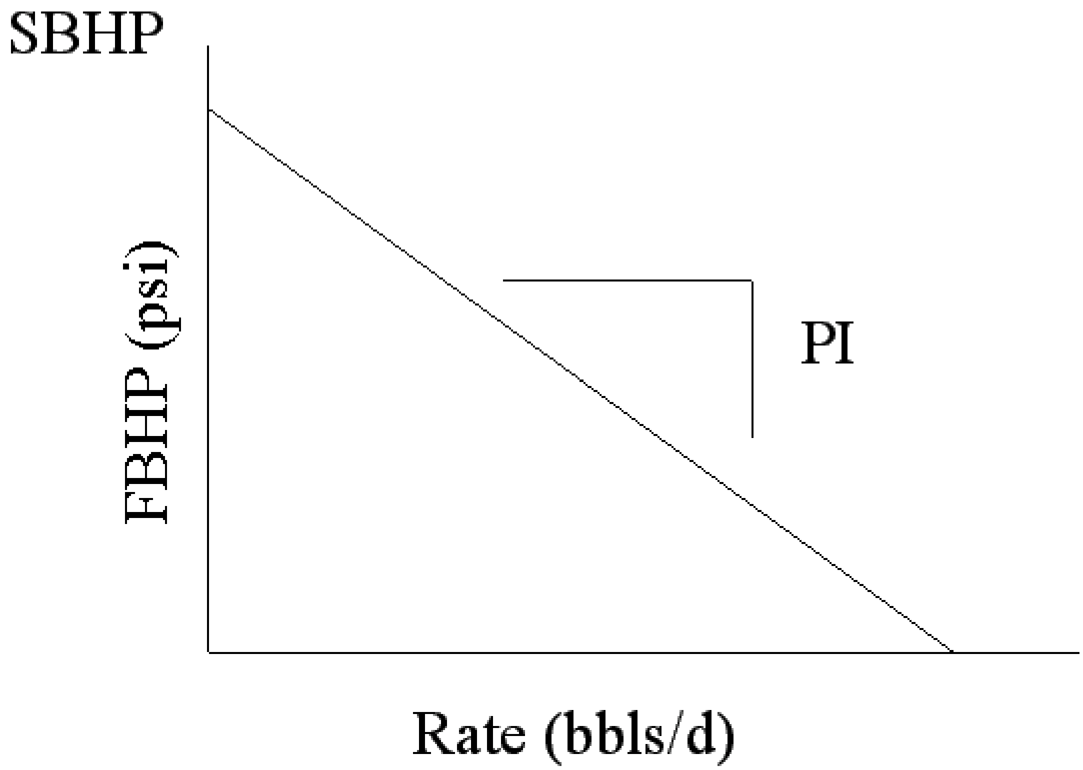
Operation

2 Inflow/Outflow

We can describe well performance in terms of inflow of liquid from the perforations:

2.1 Inflow Performance

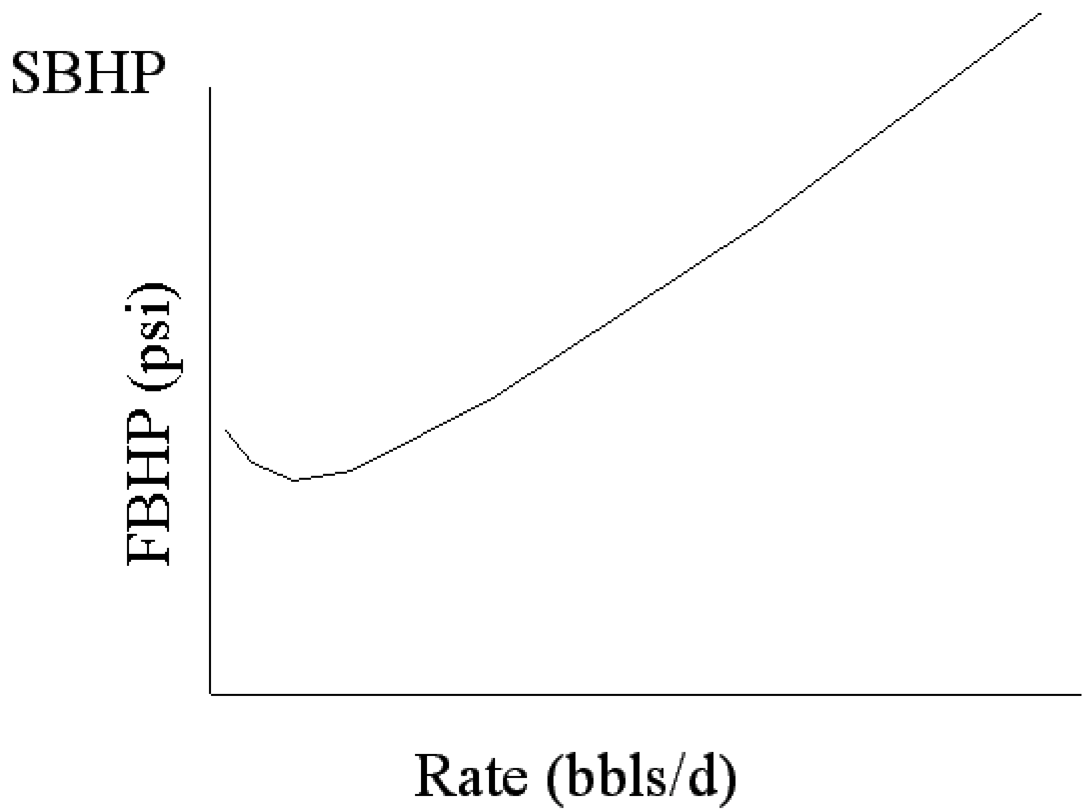
We get more liquid into the well with lower FBHP.



We can also describe well performance in terms of outflow through the well's tubing, choke and flowline:

2.2 Outflow Performance

We get more liquid out of the well with higher FBHP

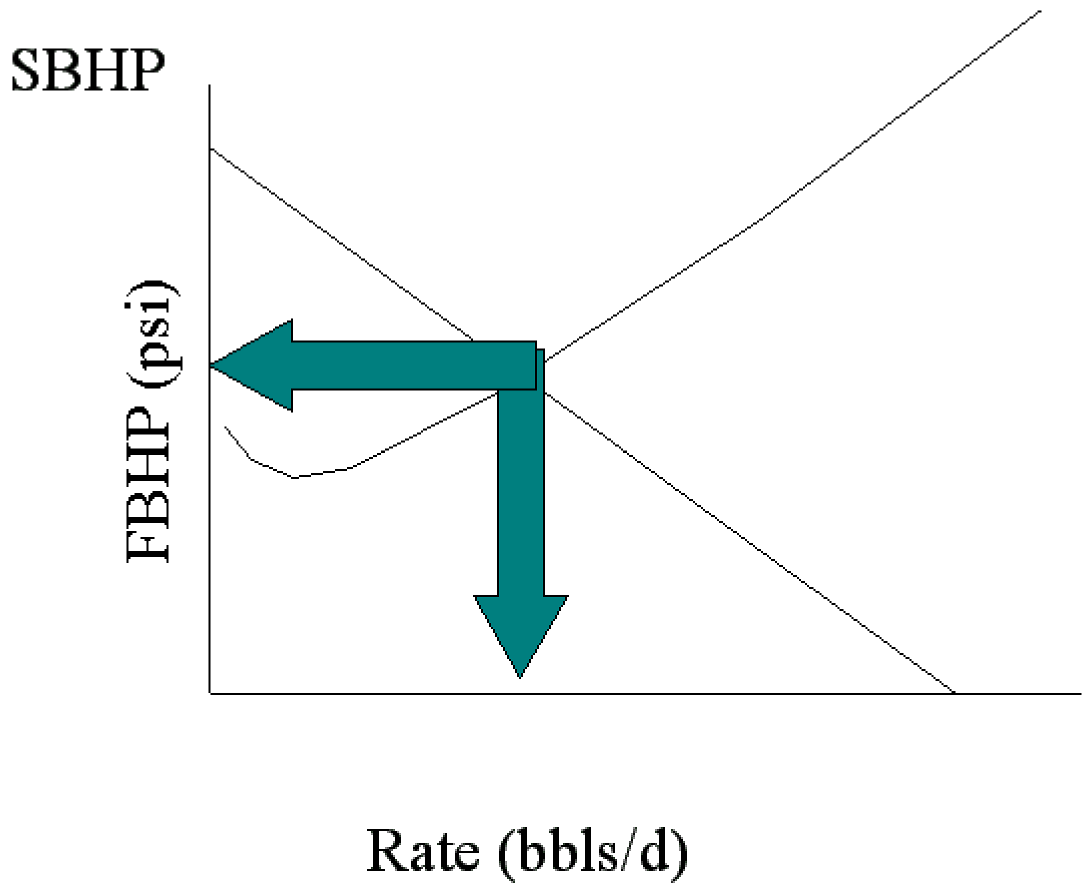


Inflow/Outflow

We can determine the productivity of a well by finding the intersection of its inflow performance with its outflow performance

2.3 Well Performance

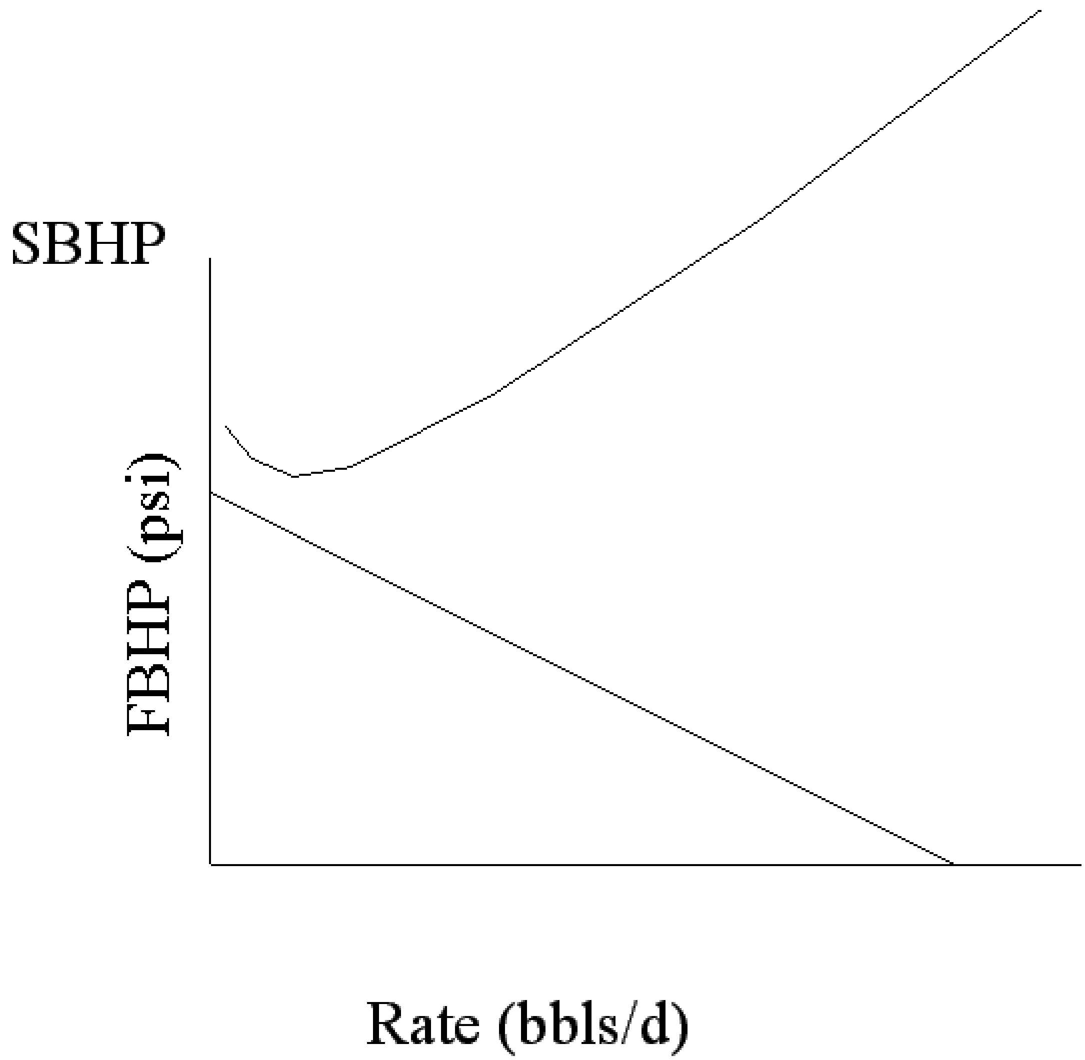
The intersection is the ***expected*** rate and fbhp



Inflow/Outflow

What happens when the outflow doesn't intersect the inflow?

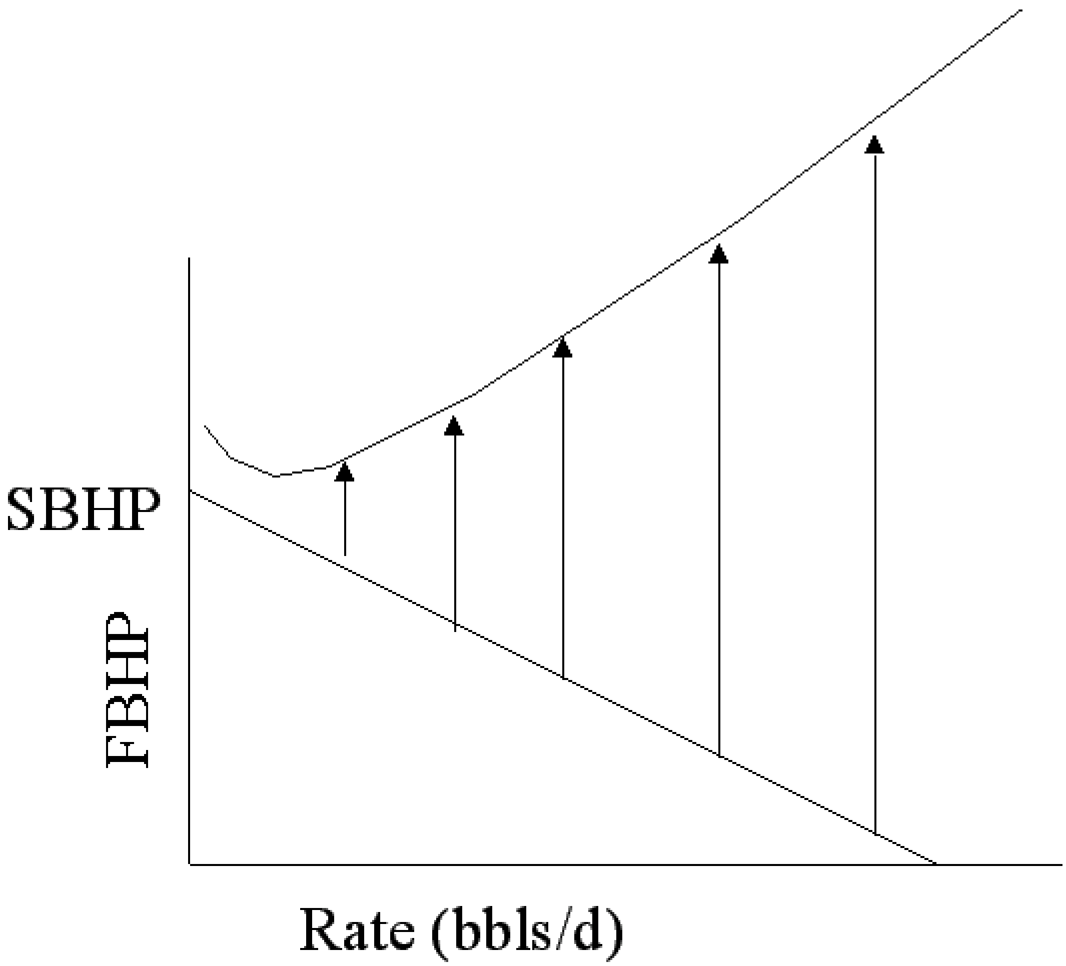
Well Performance



Inflow/Outflow

In order to get some production out of the well, we need to supply some ***energy*** to the system. It would be great if this were natural energy provided by higher inflow pressures (like by a higher SBHP).

Well Performance

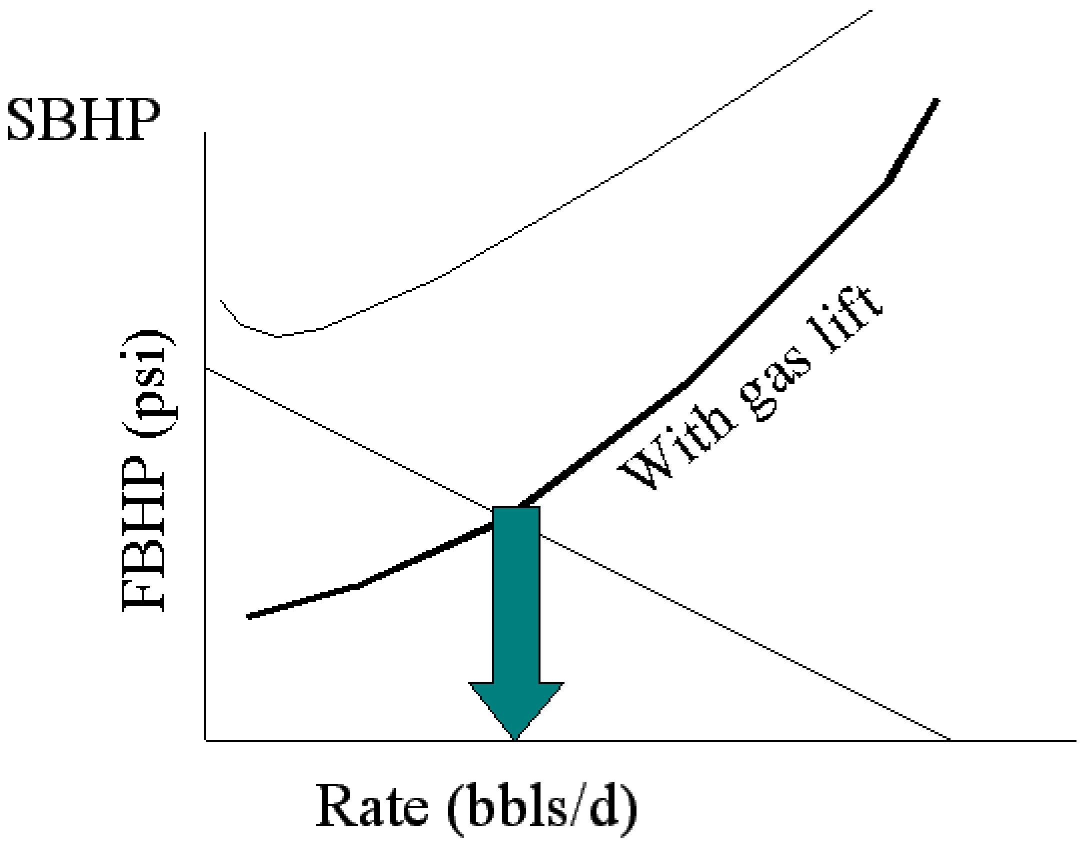


Instead we usually have to provide ***artificial lift*** to get the oil from the perfs up through the outflow system

Inflow/Outflow

One form of artificial lift used extensively is ***gas lift***.
In gas lift we inject gas into the flowing stream inside the tubing to reduce the pressure gradient. By doing this we actually lower the outflow performance curve to intersect the. inflow performance

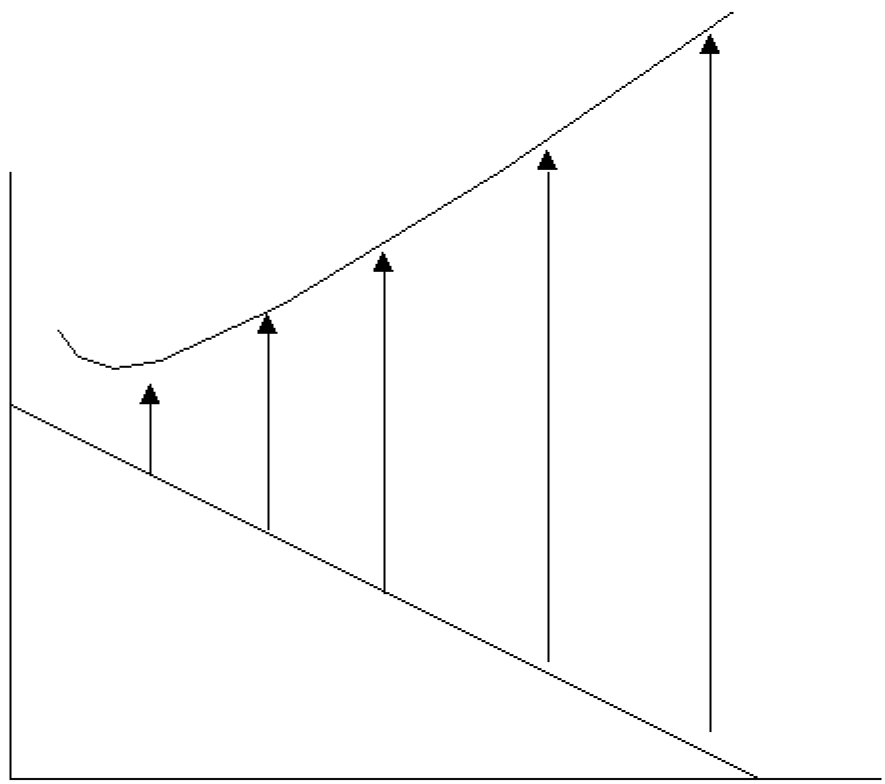
Well Performance



Inflow/Outflow

Gas lift works great in many cases, however it just can't get to either really low FBHPs or really high rates.
In these cases, we can use a ***pump*** to take liquid from the intake pressure and raise the pressure enough to pass through the outflow system.

Well Performance



One pump is called an Electric Submersible Pump, ESP.

3 The ESP System

Let's compare gas lift and ESPs

Gas Lift	ESP
Gas helps	*Gas hurts
Wide range of production rates practical	*Narrow range of production rates practical
High tolerance for sand	*Limited tolerance for sand
Run tools to perforations	No access below pump
Low opex after high capex (compressor)	*High cost (replacements), low capex.
Commodity pricing	Vendors make $$
Innovation low	Innovation high
Gets inefficient	*Catastrophic failure

*** These items limit the number of ESPs in GOM**

The ESP System

ESPs are best for these conditions:

Moderate to very high rates (500 - 50,000 bbl/d)

Low gas liquid ratios (GLR < ~200)

High drawdown (to FBHP=150 psi) is OK.

Few solids (e.g. sand, scale)

Not too hot (temperatures above ~200^{o} may limit horsepower, problems above 300^{o}).

Not too deep (~12000' max.)

Stable inflow performance and good data available for design.

High quality supply of HVAC electricity.

Continuous operation (few stop/starts)

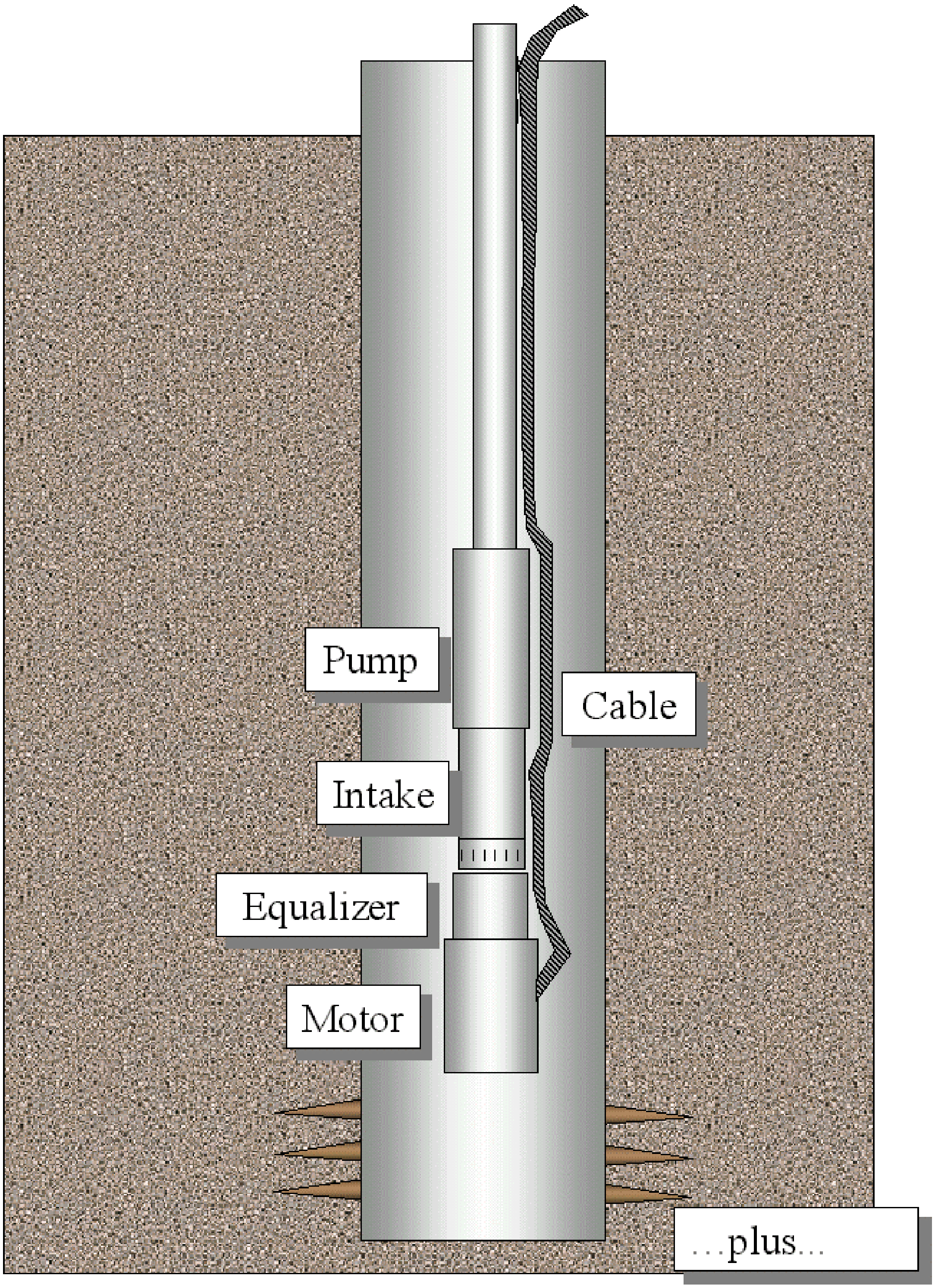
Larger casing sizes are better.

Deviation (even horizontal) is OK, doglegs are not OK.

Large numbers of installations so rig crew and operators can get up the learning curve quickly.

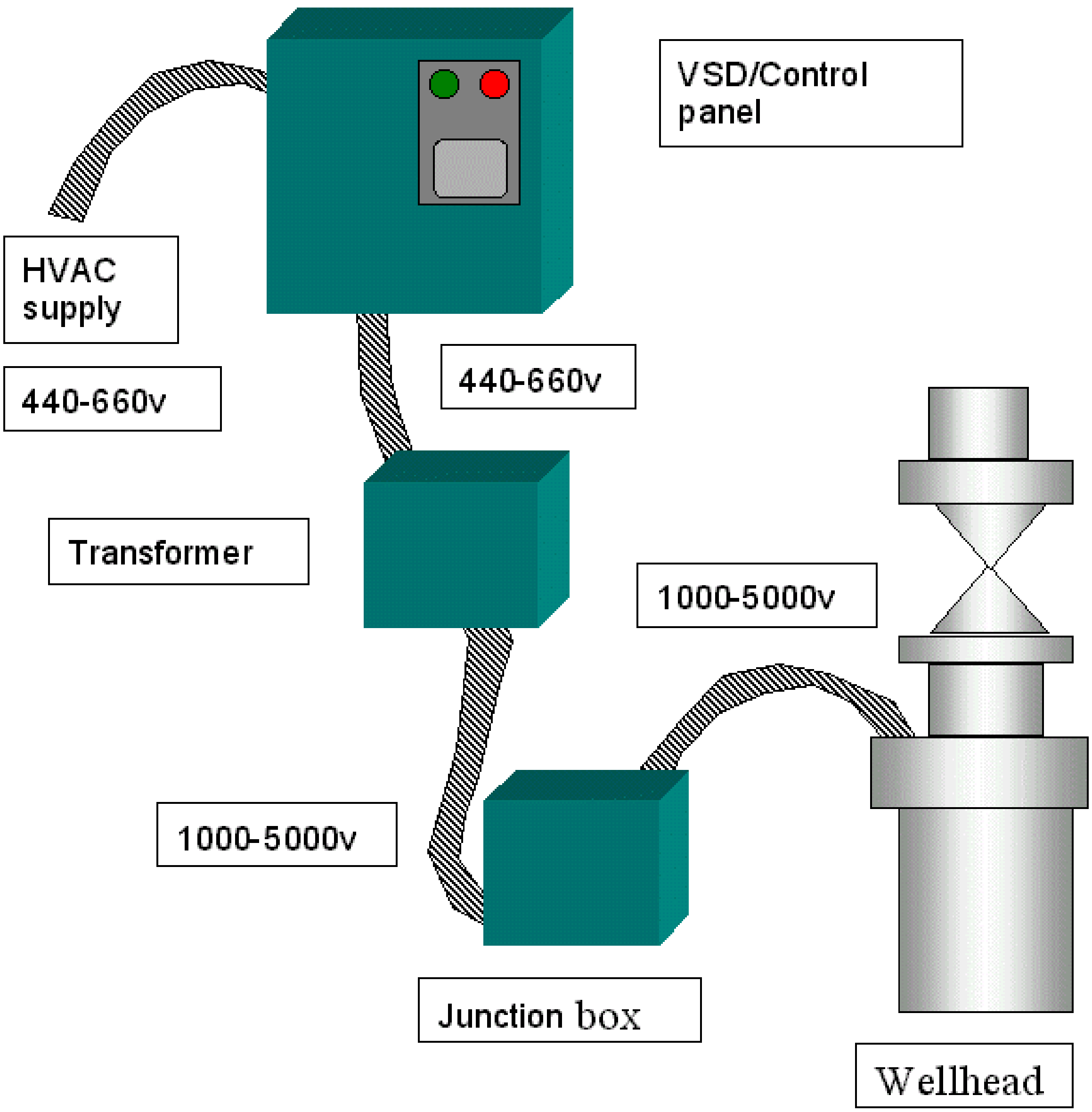
The ESP System

The pump itself is only the beginning of the story, so when we refer to an ESP, most of the time we refer to the entire ***system,*** composed of:



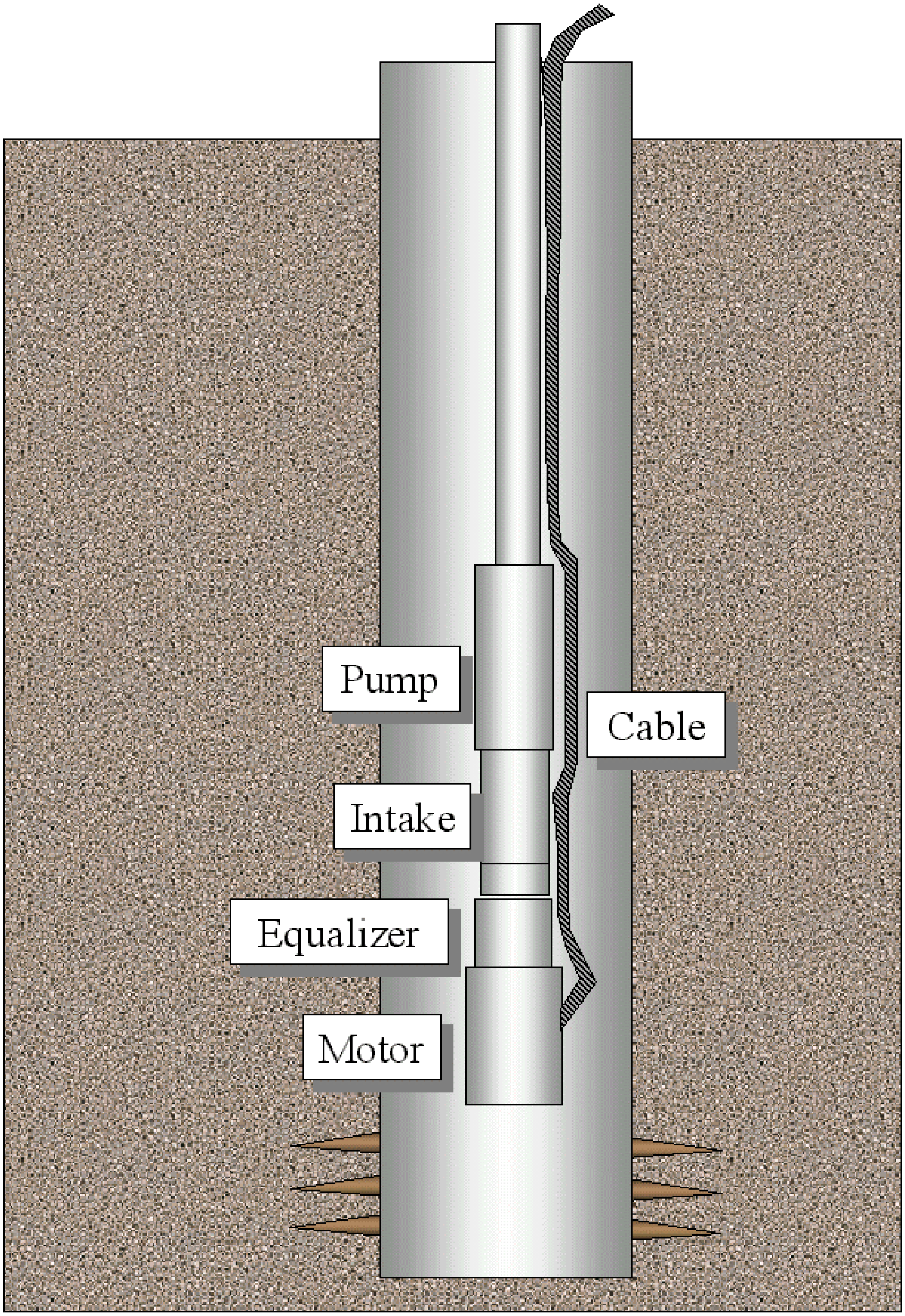
The ESP System

Some of the most important pieces of the system are above ground:



The ESP System

Now let's look at each piece of the system.

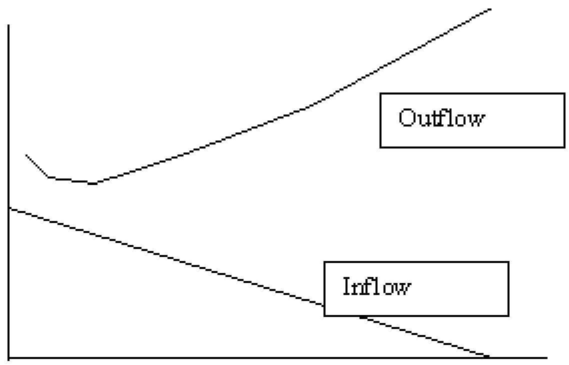


3.1 ESP System Questions

"We get more liquid into the well with lower FBHP"
Which part of the system is this?
a. Inflow
b. Outflow
c. ESP

"We get more ____________ with ______"
a. We get more for our money with government help
b. We get more out of life with Shell People Services on our side
c. We get more liquid out of the well with higher FBHP

Find the _______ with the intersection of the inflow and outflow curves.
a. maximum flow rate and FBHP
b. optimum flow rate and FBHP
c. expected flow rate and FBHP



The well above will:
a. not make any money
b. not flow
c. be a candidate for artificial lift
d. all of the above

Artificial lift provides energy to the reservoir to help wells flow
True or False. Why?

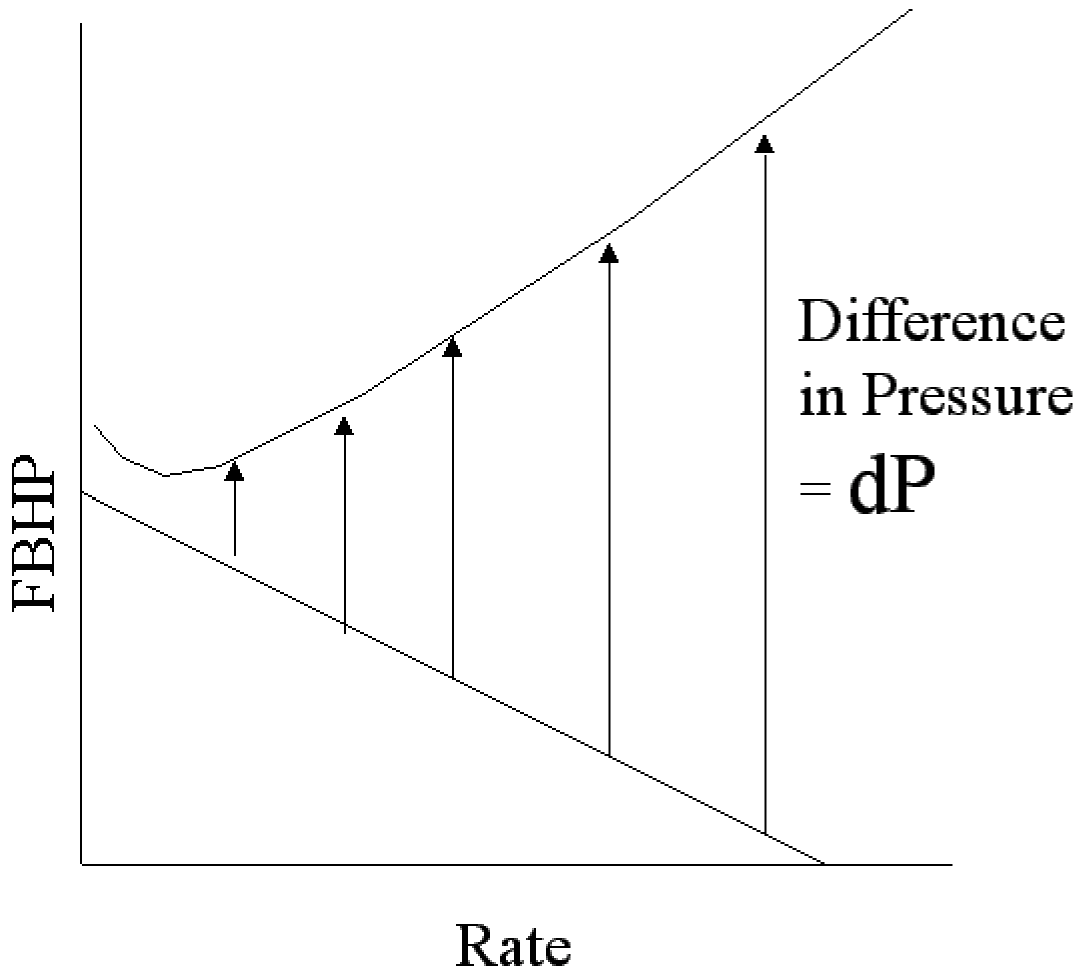
Which artificial lift system sounds better for each well below (gas lift or ESP):
#1: Set up to recomplete through tubing
#2: GOR 2000
#3: FBHP 500 psi at 10000’
#4: Subsea well

You hear a crew member say “My VSD is broken.” How many rigs do you need to fix this?
0
1
2

You hear a crew member say “My ESP cable is broken.” How many rigs do you need to fix this?
0
1
2

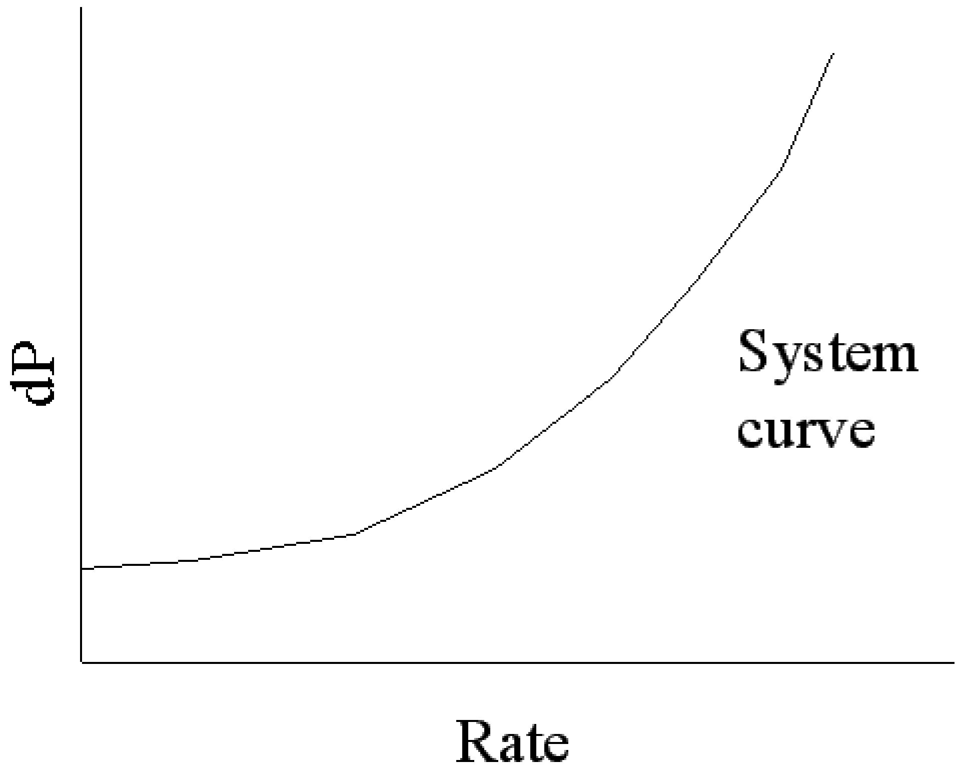
4 ESP – Pump

We have already discussed how the pump must create the pressure difference between the inflow and the outflow pressures.



ESP – Pump

By re-graphing the difference in pressure between the two curves, we get the following plot:



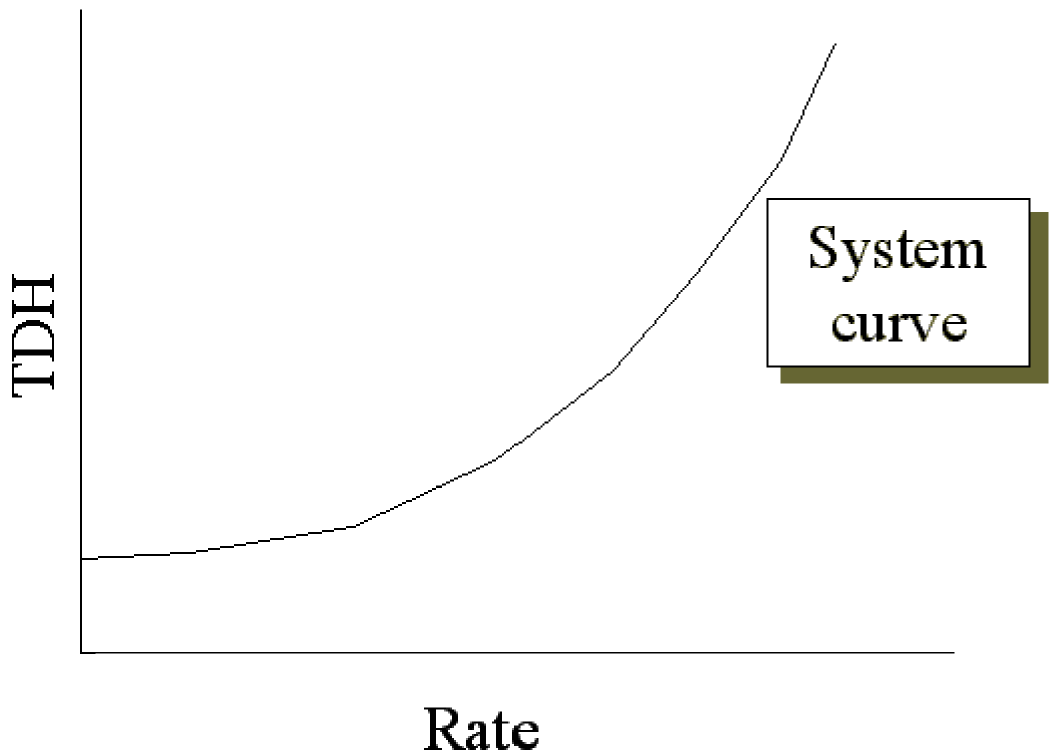
We call this the **system curve** because it includes everything to do with our system from the reservoir to the end of the flowline, ***except for the pump***.

ESP – Pump

Head is a measure of the vertical feet of a liquid that a given pressure can support.

Head (ft) = Pressure (psi) / fluid gradient (psi/ft)

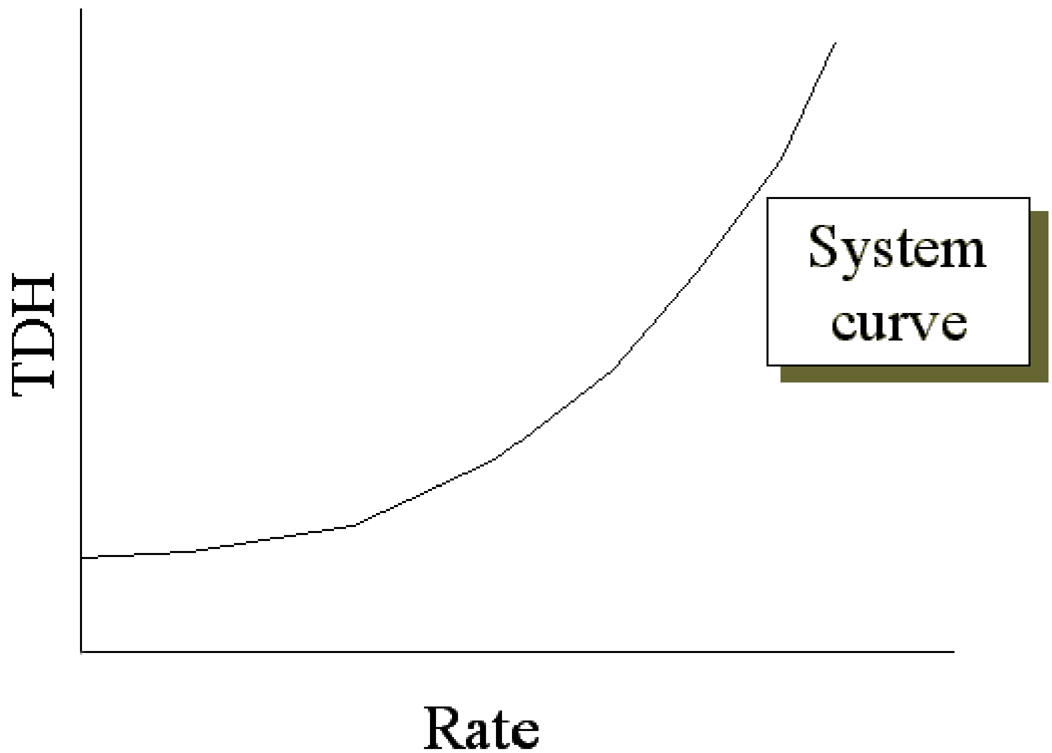
Since centrifugal pumps are 'constant head' devices, it is convenient to convert the system curve to be in terms of head.



Various pressures in the system add up to the total developed head, or TDH.

ESP – Pump

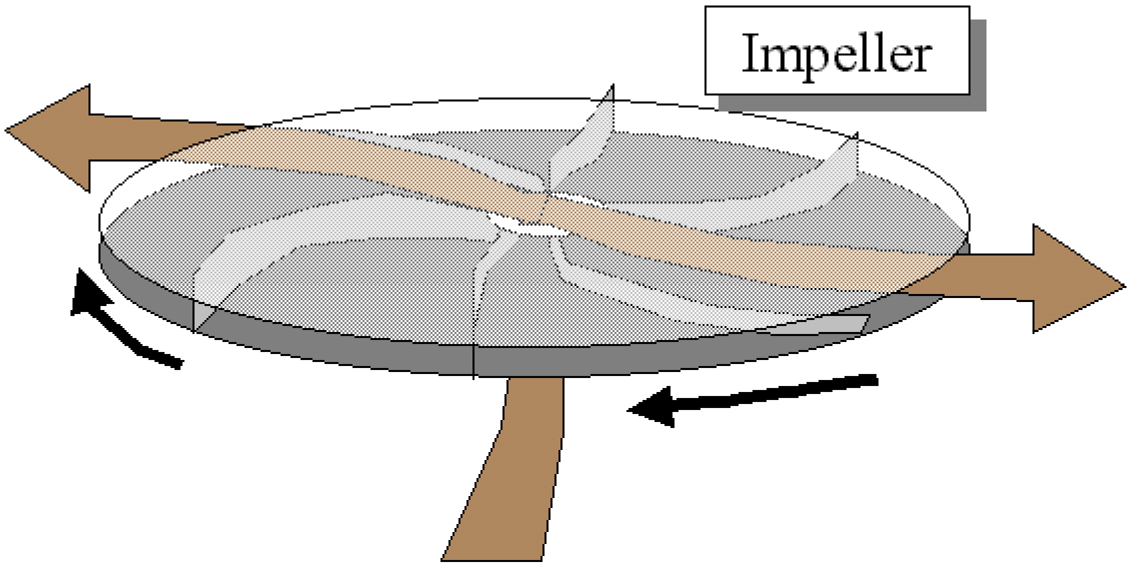
The system curve is ***the head that the pump must supply*** in order to produce a given rate.



ESP – Pump

The heart of an ESP pump are its ***impellers***.

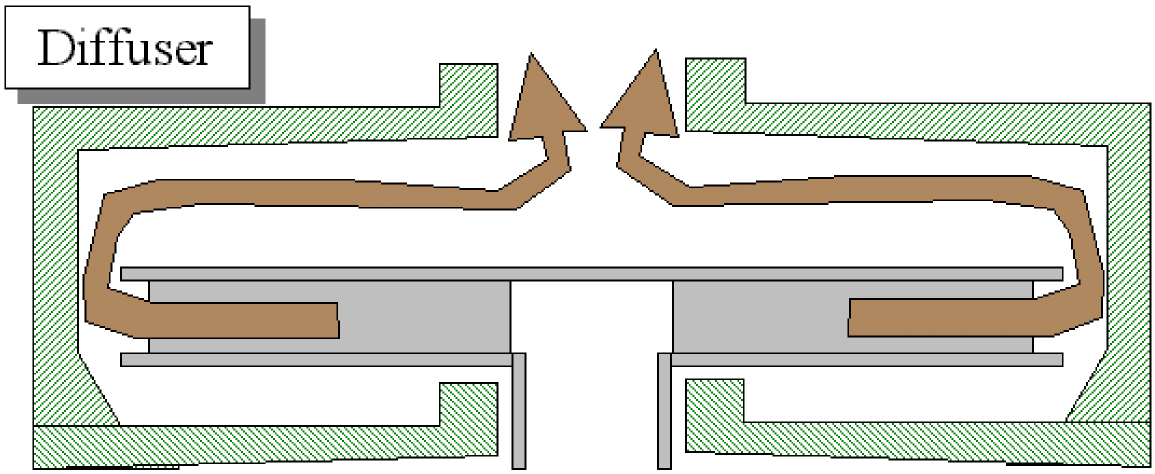
These spin at high speeds sucking liquid up in the center, imparting rotational energy to the liquid and throwing the liquid out at high speed.



The liquid that gets thrown out of the impeller makes a room for more liquid that gets pulled in through the center.

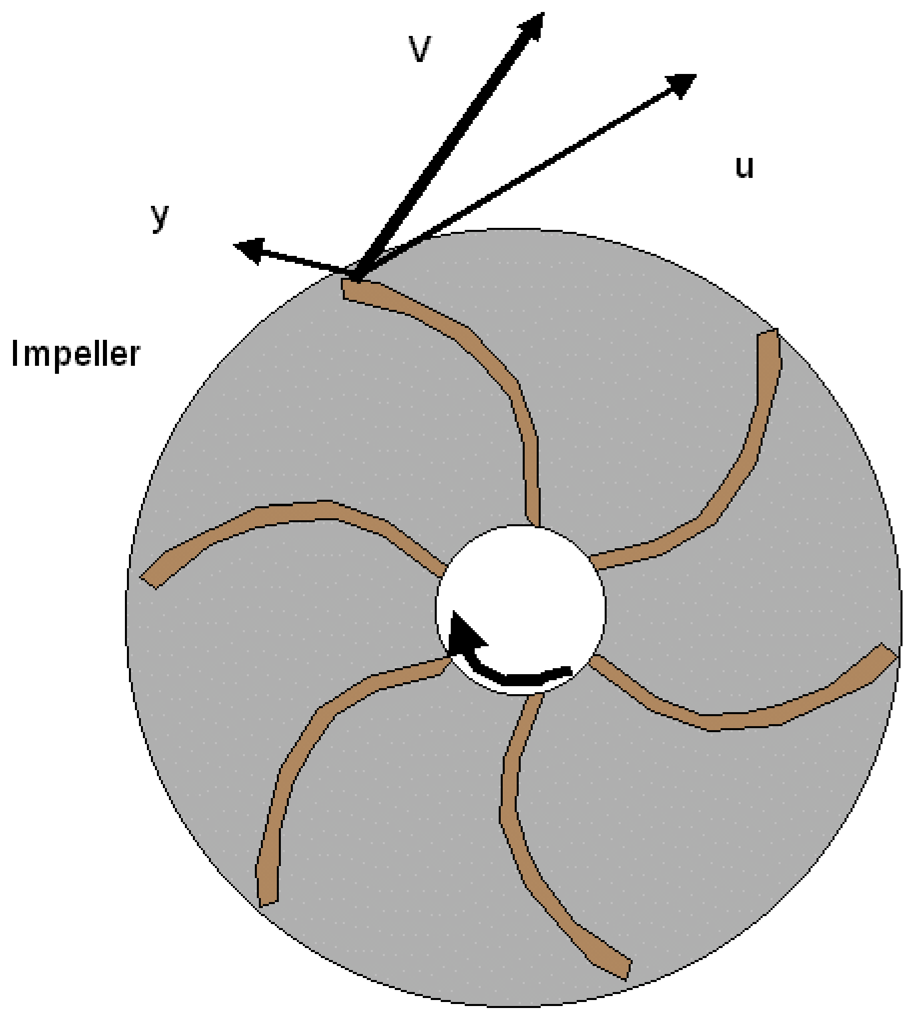
ESP – Pump

In order to properly use the energy that the liquid now has, the pump has diffusers that slow down the liquid and turn it. This changes the velocity of the liquid into head/pressure.



ESP – Pump

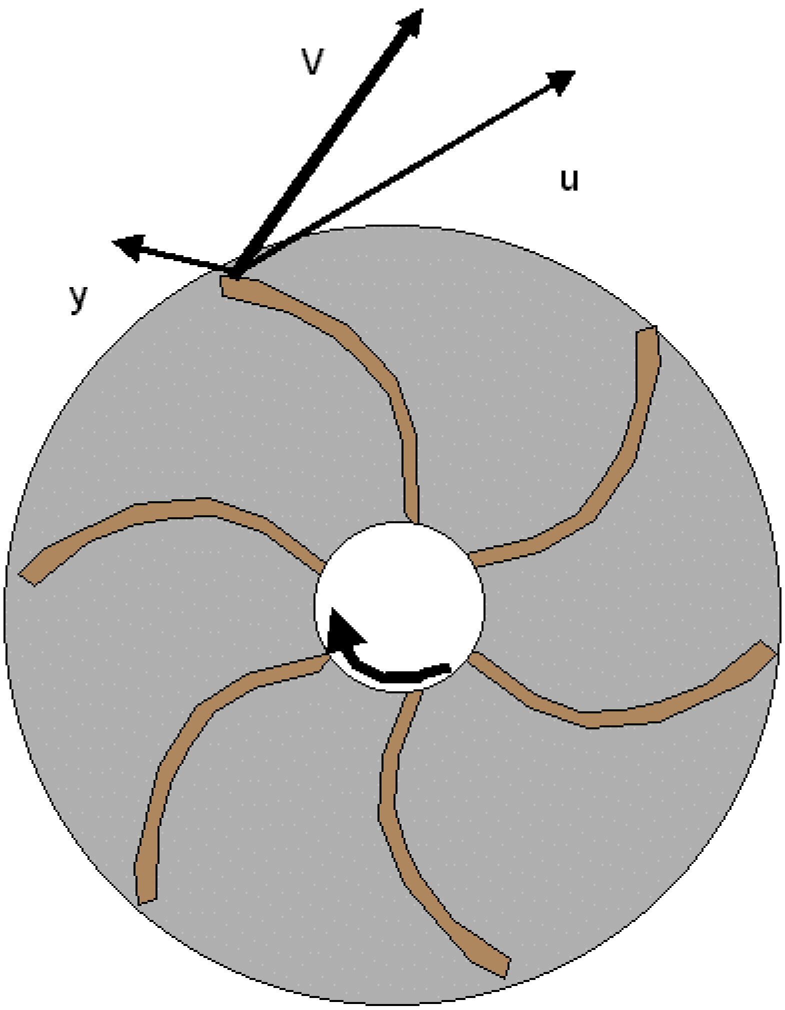
Head generated by the pump can be found by looking at the change in velocity generated by the pump, V. The two components that make this up are the velocity in the direction of the tip of the impeller, u, and along the impeller, y.



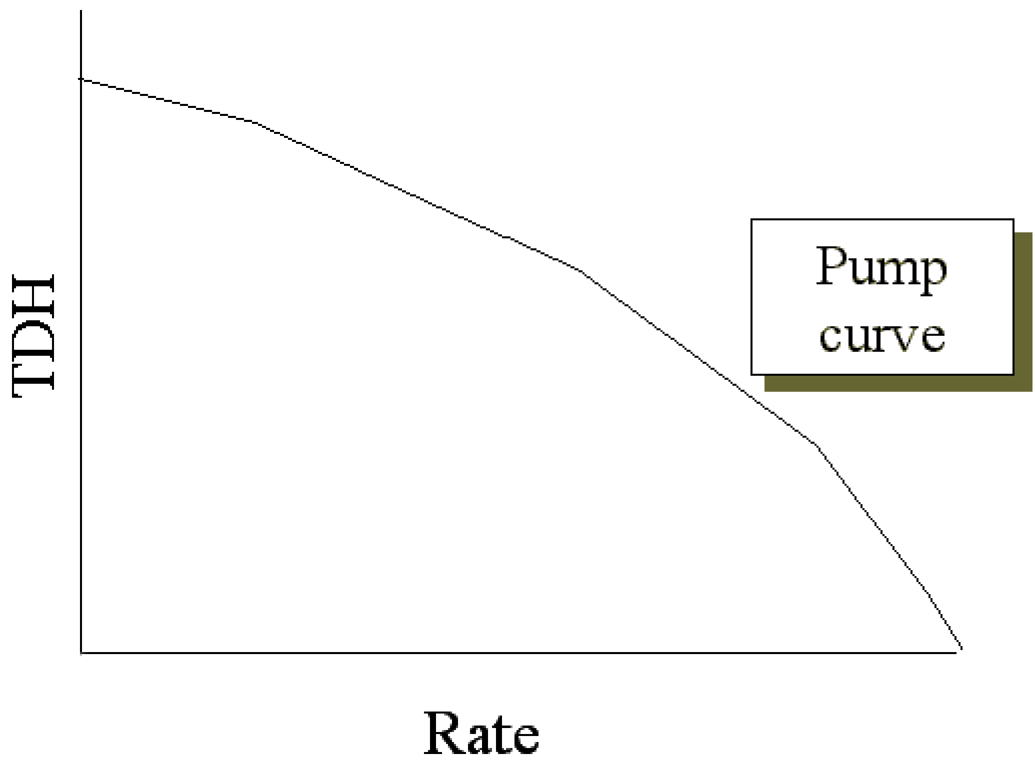
ESP – Pump

Only the component u contributes to head.

As the flowrate through the pump increases, so does component y, which tends to decrease component u, and thus the head generated.



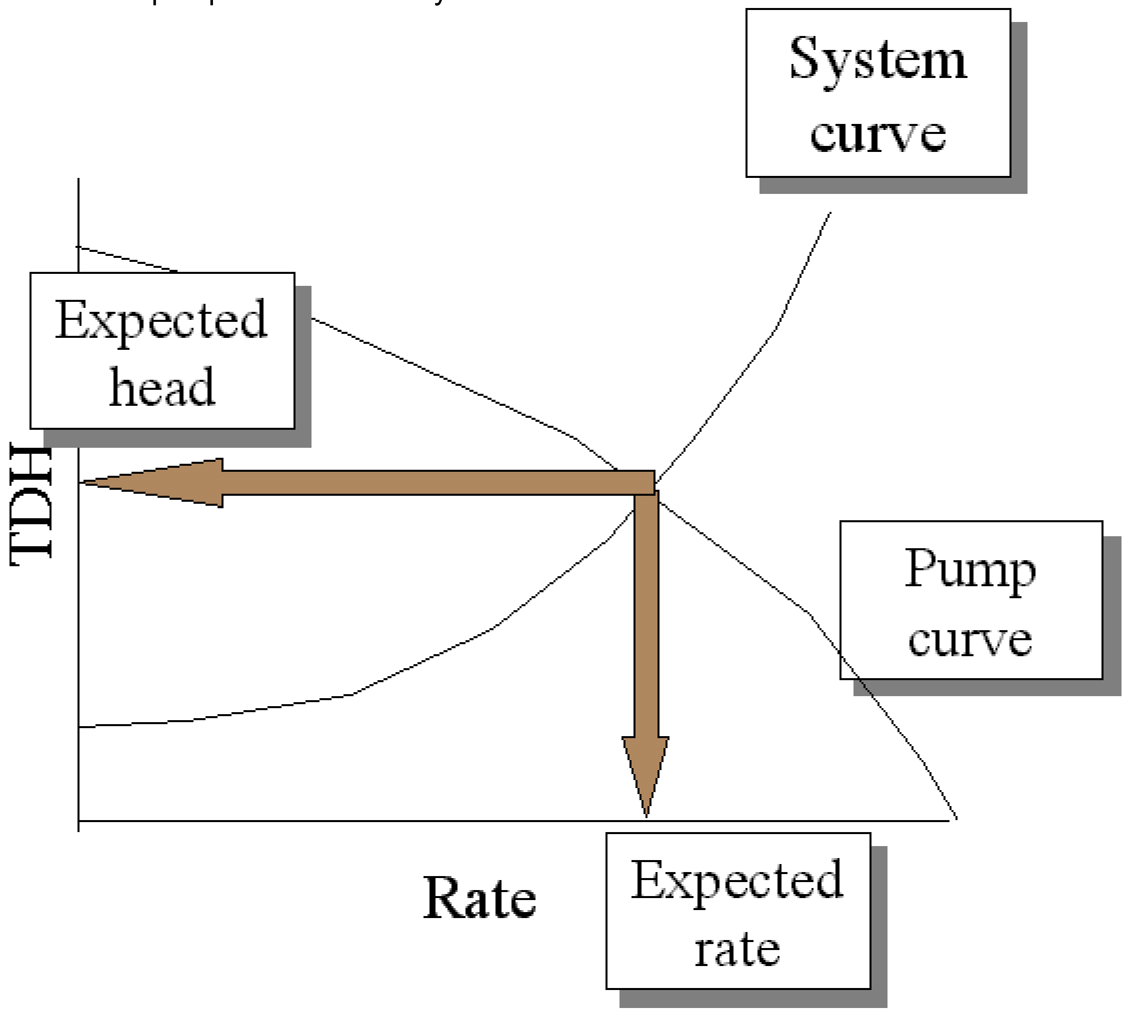
Thus, for a given impeller at a given rotational speed, the more rate, the less head. You can see the result as a plot of the ***pump curve*** on the TDH vs Rate graph:



The pump curve is ***the head that the pump can supply*** at a given rate (and rotational speed).

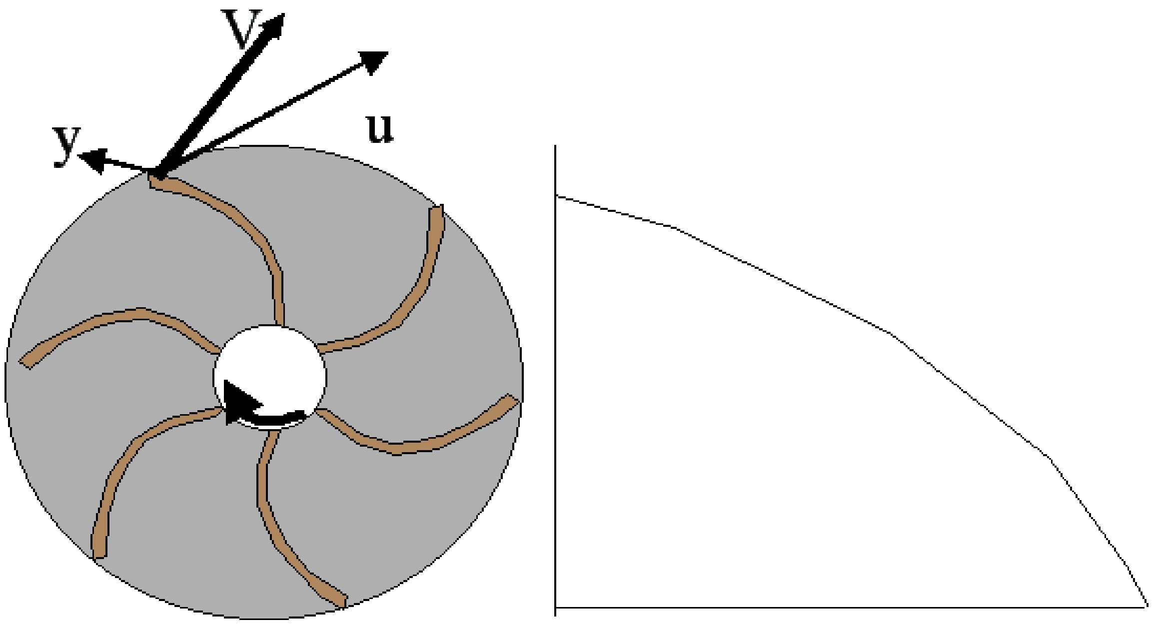
ESP – Pump

The ***expected operating point*** for the whole system can be found at the intersection between the pump curve and the system curve.



ESP – Pump

The pump curve is not affected by the specific gravity of fluid it is pumping. At a given rotational speed, the same head is generated



ESP – Pump

This creates a few interesting characteristics of centrifugal pumps.

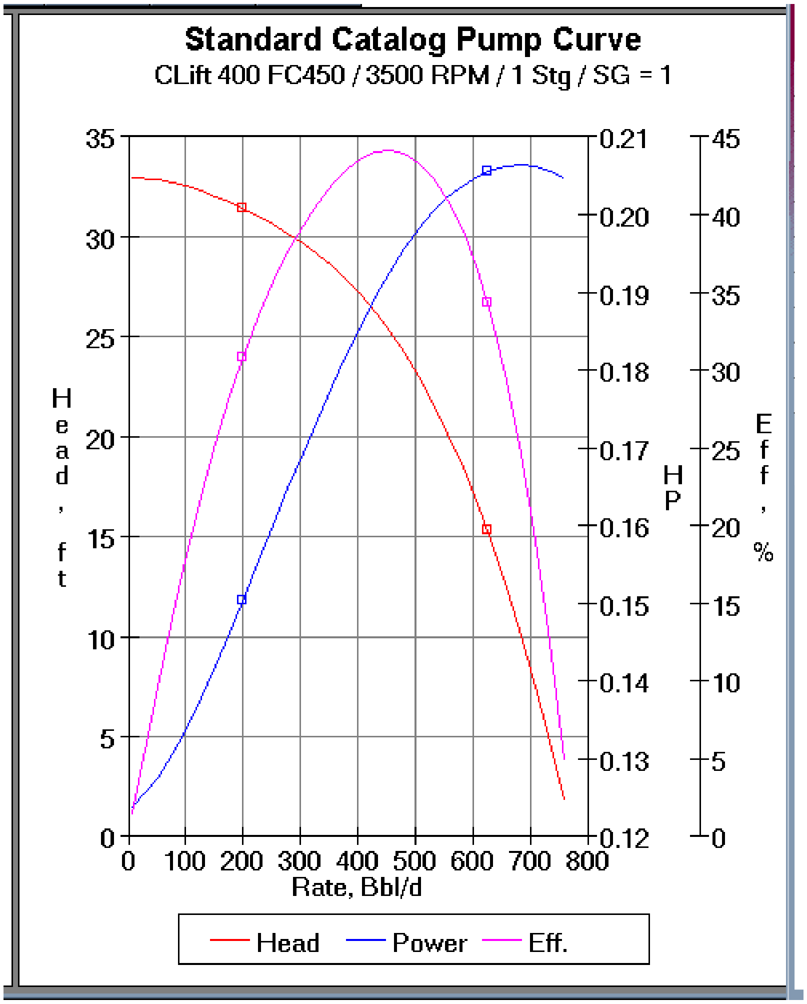
- ESP manufactuers and customers can discuss the pumps only in terms of head, without needing to know density of the fluid pumped.

- Manufacturers can test the pumps with fresh water only.

- Vendor catalogs have pump curves only for fresh water.

ESP – Pump

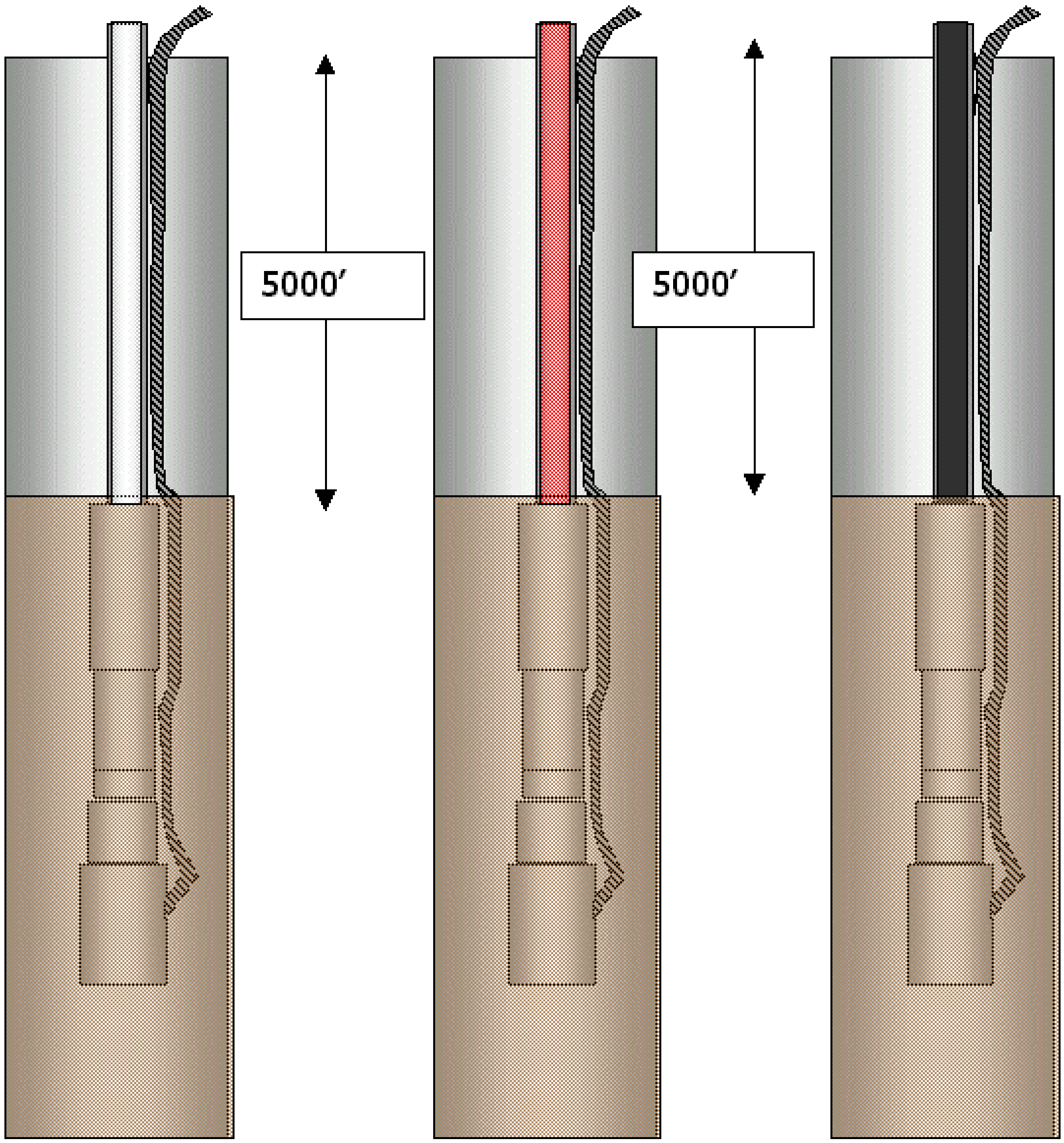
Here is the pump curve from the vendor's catalog for the pump in SMI-130 A-7.



Along with the head curve are given the horsepower and pump efficiency curves.

ESP – Pump

The same pump at the same rotational speed will generate the same head, regardless of the density of the fluid pumped.



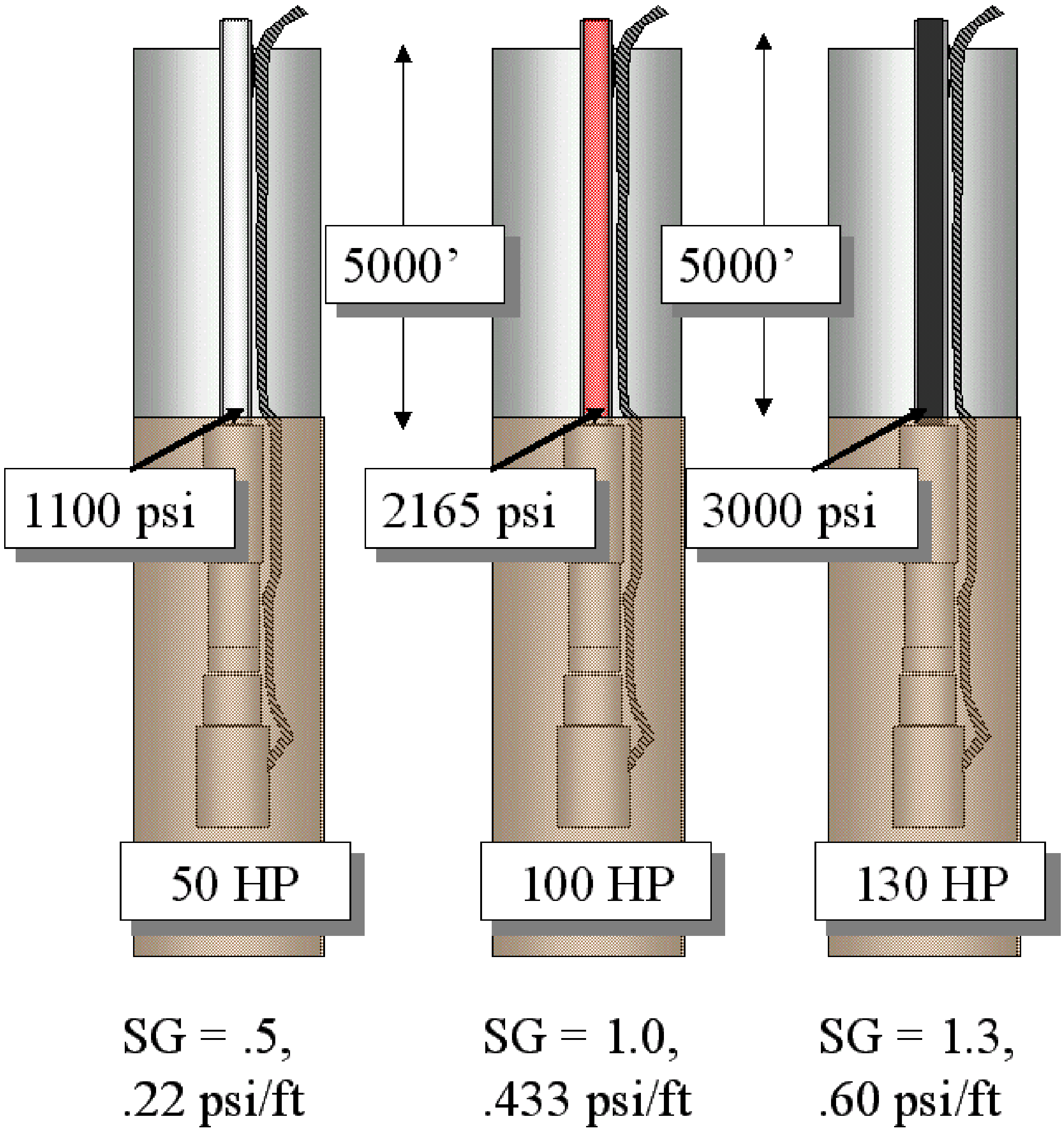
SG = .5,
.22 psi/ft

SG = 1.0,
.433 psi/ft

SG = 1.3,
.60 psi/ft

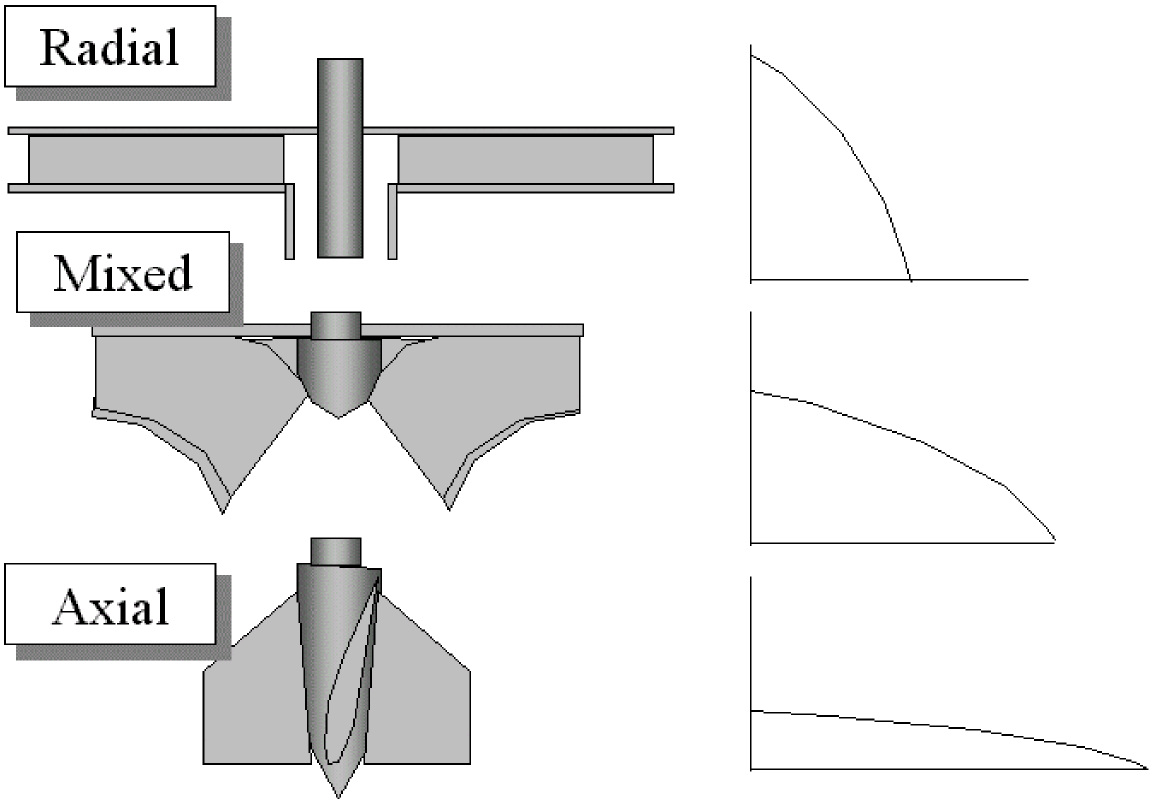
ESP – Pump

However, that does not mean that the pressures or horsepower required are the same!



ESP – Pump

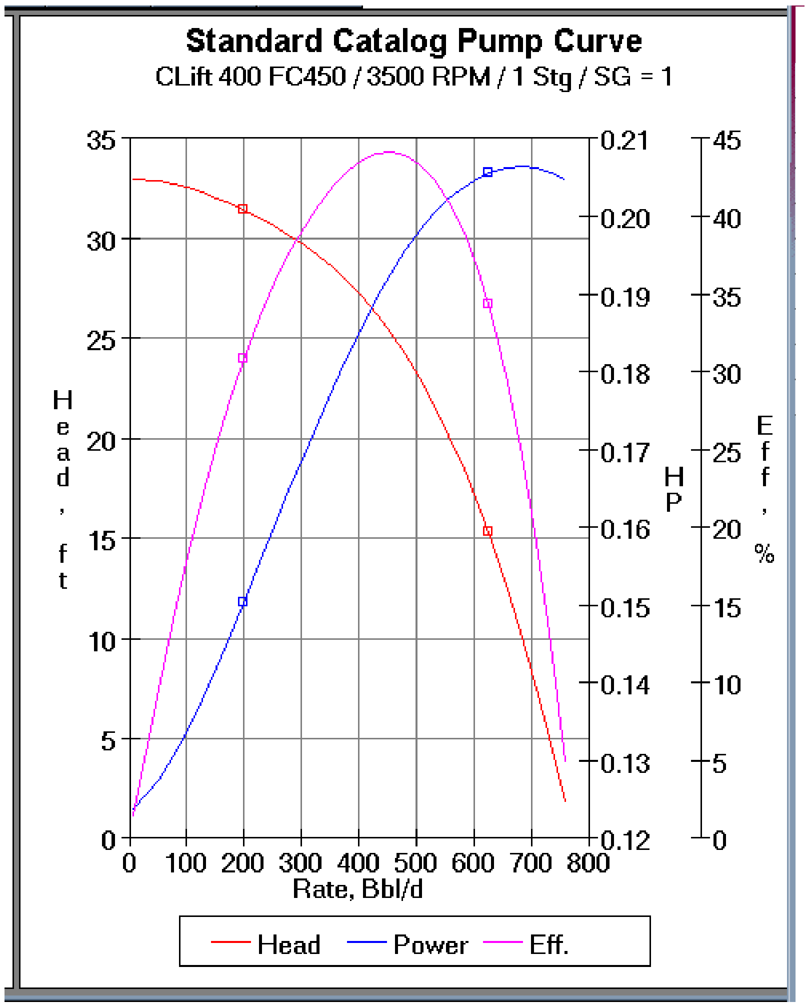
The shape of the impeller influences the fundamental shape of the head rate curve.



Most pumps use ***radial*** impellers, but they may tend toward ***axial*** shape to pick up flowrate at the expense of head.

ESP – Pump

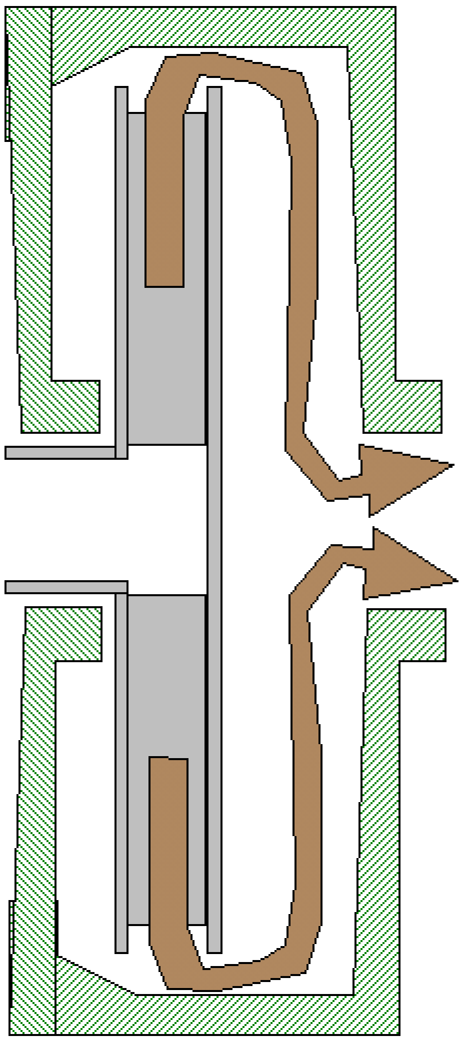
Note that the head generated as shown in this catalog pump curve is approximately 25 feet at about 450 bbls/d.



That is for a single pump ***stage***. We need thousands of feet of head to get liquid to the surface in most wells.

ESP – Pump

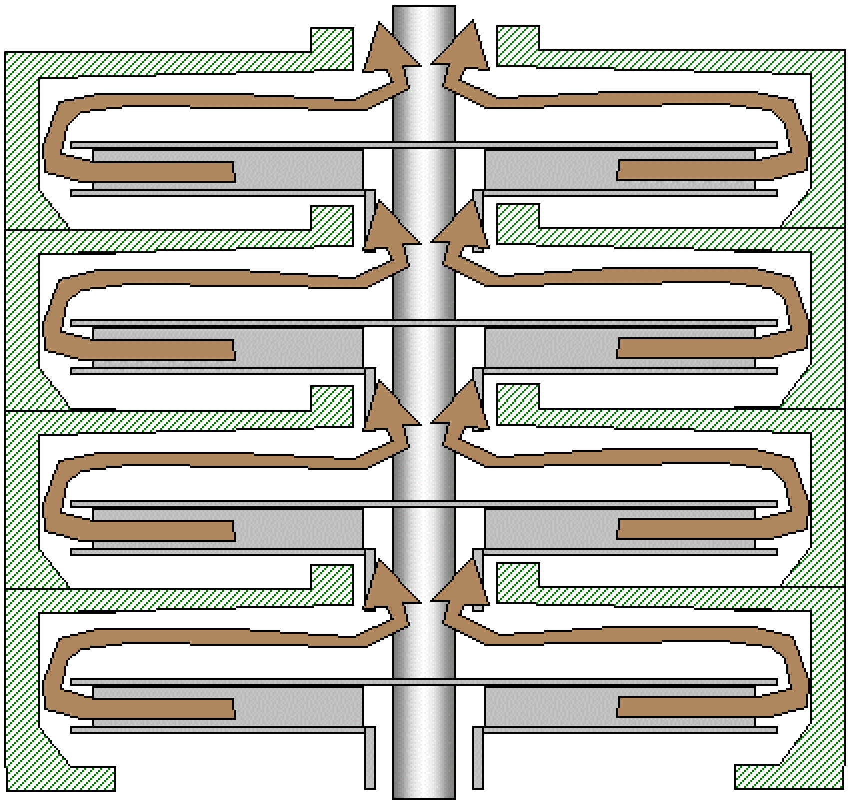
To generate sufficient head, traditional centrifugal pump manufacturers create a single, very large impeller. This is the kind of pump used in surface facilities (e.g. waterflood pump).



The efficiency (and cost) of this pump is high.
However, this is not a suitable size and shape for putting into a well.

ESP – Pump

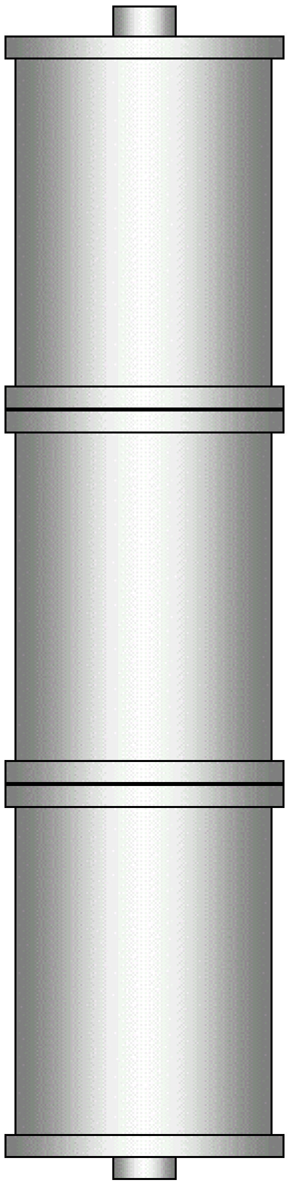
In order to create sufficient head to lift liquid to the surface in a normal well, we need to stack the stages. Each stage feeds into the one above. Each stage adds a small increment of head.



Most ESPs have hundreds of stages driven by a single shaft. The size and cost of each stage is fairly small.

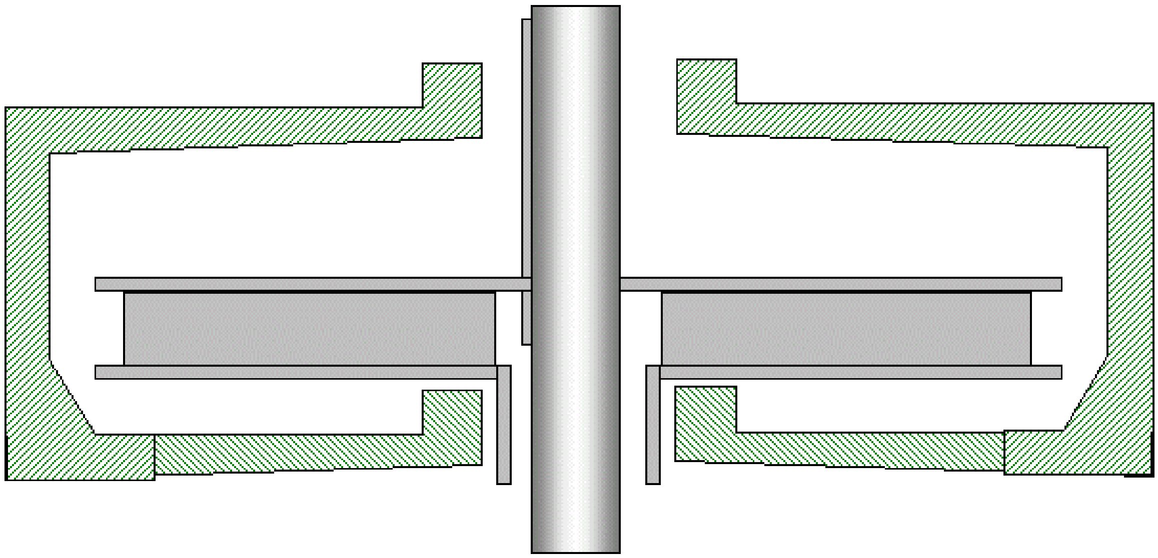
ESP – Pump

When the length of the stacked stages gets unwieldy, the stages can be grouped into multiple housings.



ESP – Pump

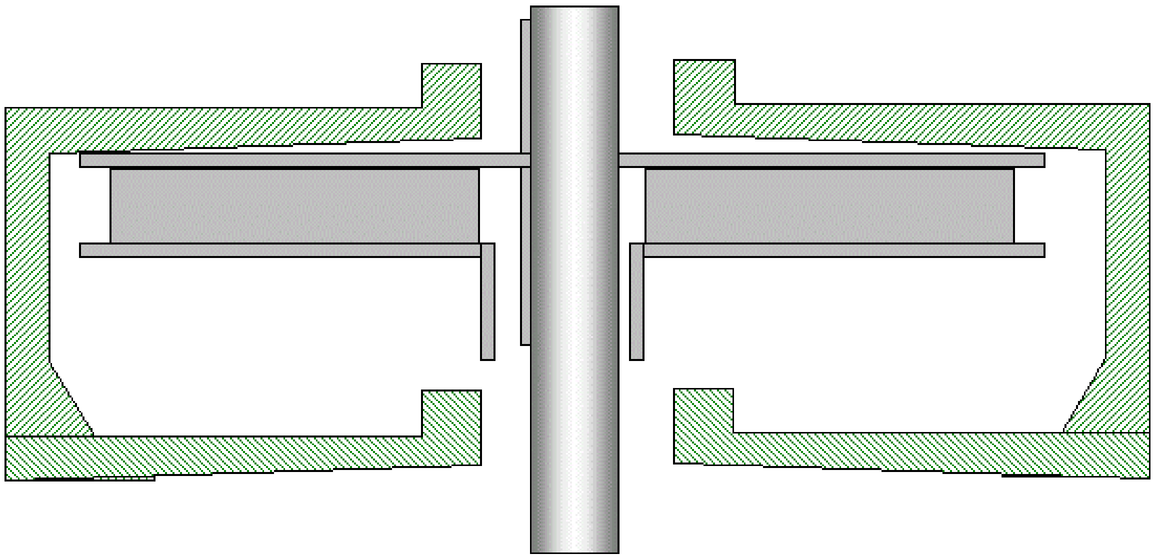
In most ESPs the impellers are keyed to the shaft in the rotational direction, but are free to move up and down the shaft. These impellers are ***floaters***.



They usually hover inside the housing, ideally with slight downthrust on the wear surfaces below the impeller. The forces acting on the impeller are balanced.

ESP – Pump

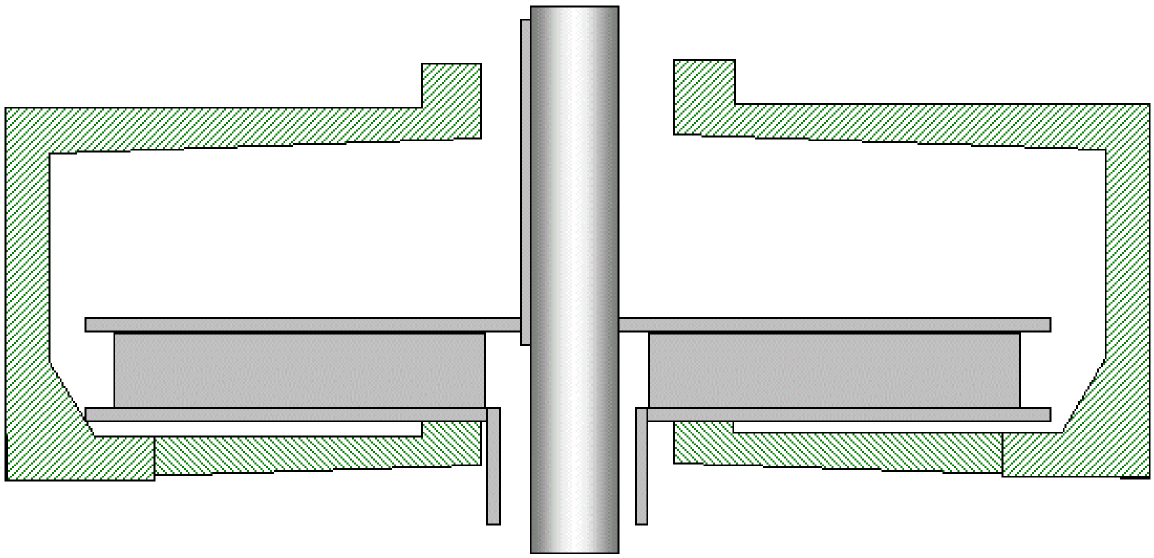
If the flowrate is too high through the pump, the impellers will be pushed to the top of the housing and will suffer wear. This condition is called ***upthrust***.



The wear will cause inefficient operation and may induce vibration that leads to pump failure.

ESP – Pump

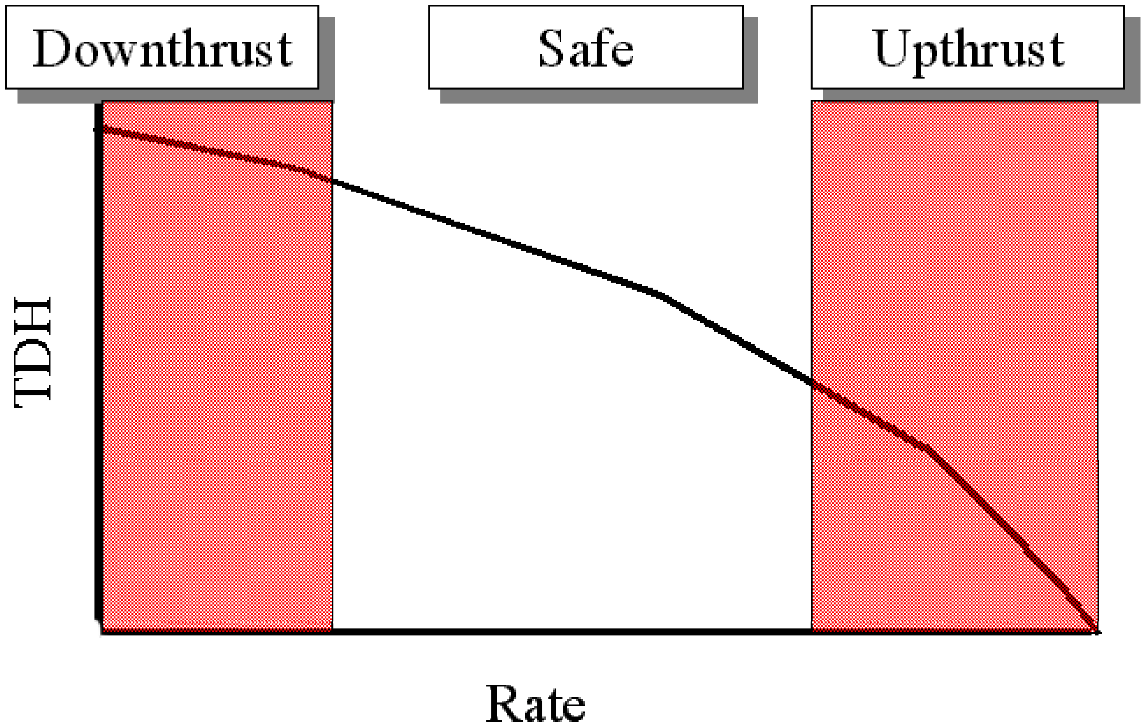
If the head is too high for the pump, the impellers will be pushed to the bottom of the housing and will suffer wear. This condition is called ***downthrust***.



Pumps are designed for some downthrust. However, if excessive the wear will cause inefficient operation and may induce vibration that leads to pump failure.

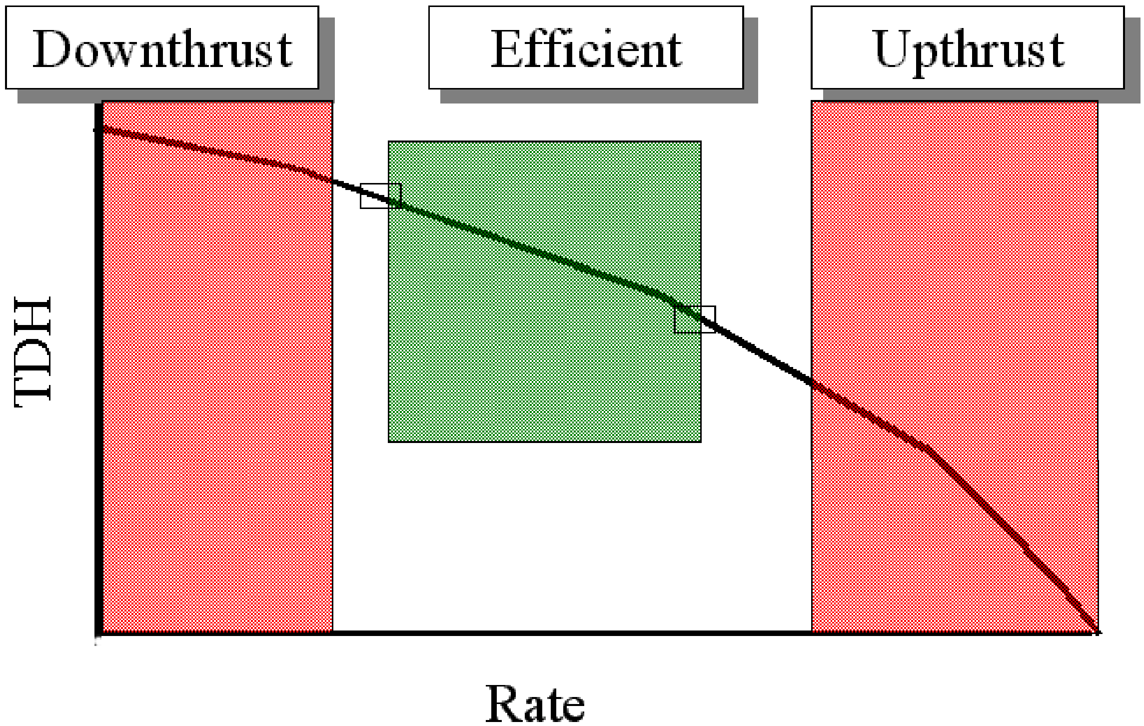
ESP – Pump

These regions can be shown on a pump curve.



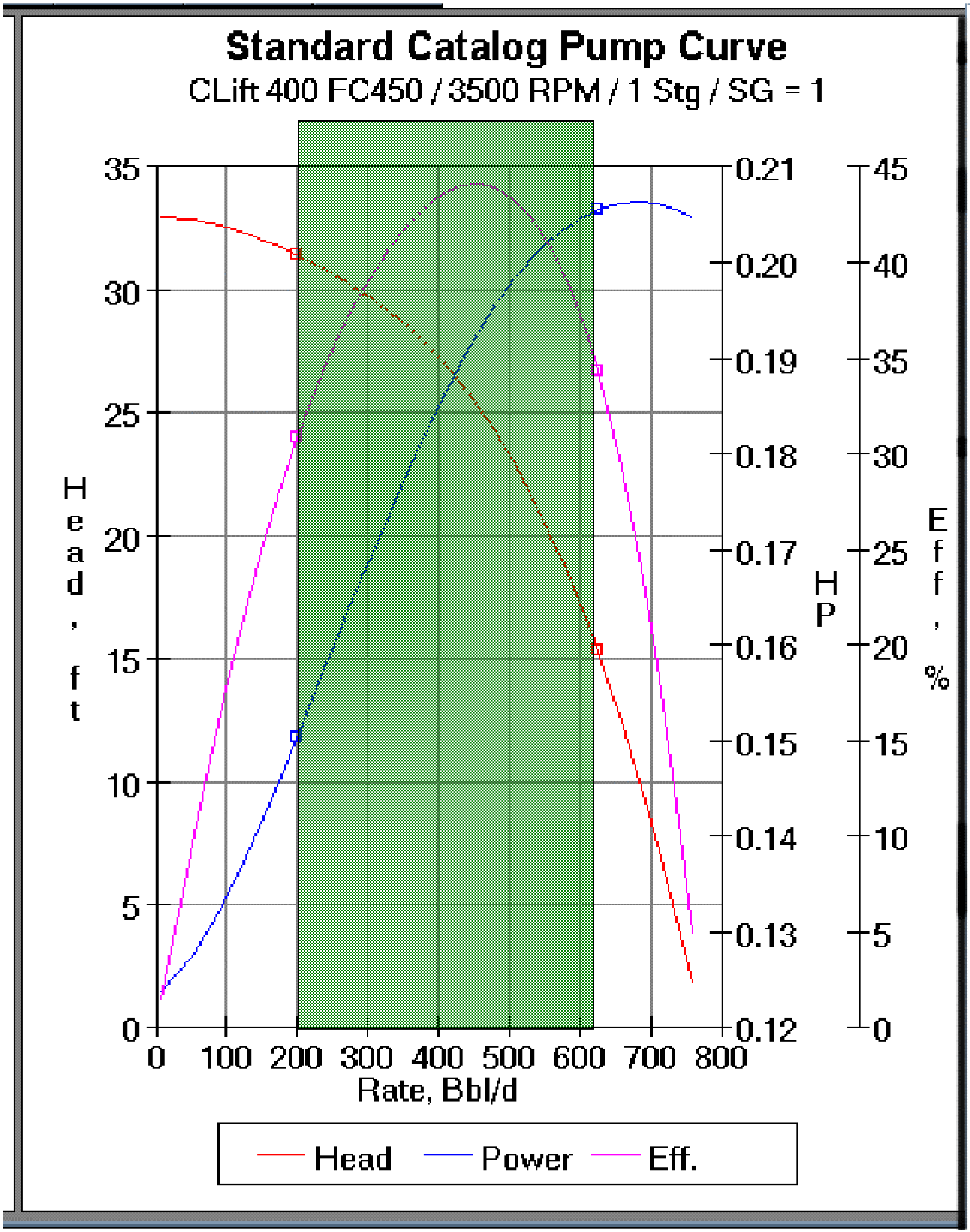
ESP – Pump

Vendors show an operating range on their pump curves that do not define the safe range, but a range inside of the highest efficiency.



The relationship of the most efficient range to the danger areas of up and downthrust is not known in most pumps, so the efficiency limits are used instead.

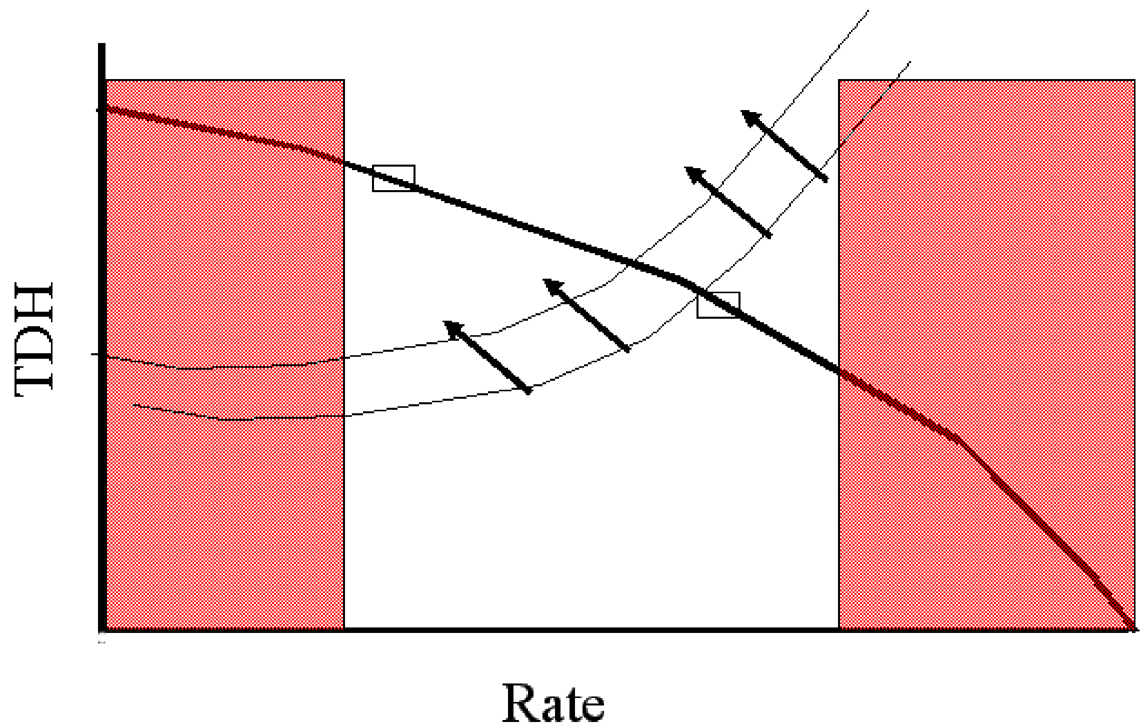
ESP – Pump



SubPump shows the recommended operating range by marking it with small squares at the upper and lower limits on each curve.

ESP – Pump

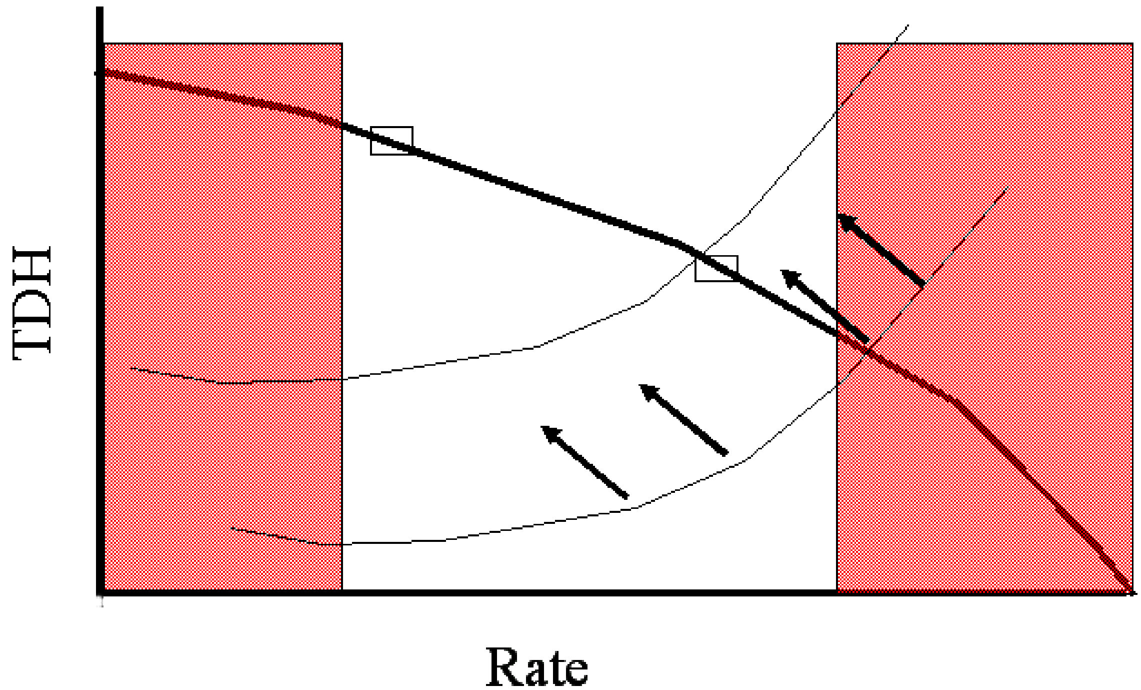
Most engineers will design pumps to operate closer to the upthrust region initially.



As the reservoir pressure declines the system curve will naturally move toward the center of the efficient region.

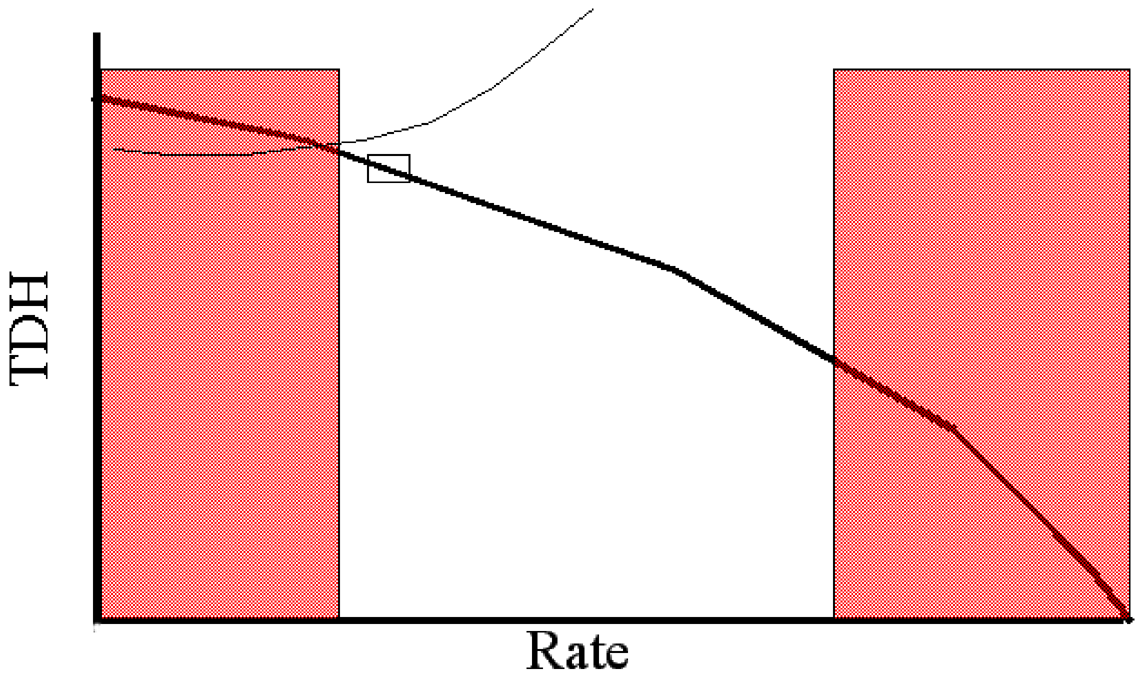
ESP – Pump

Also if the inflow performance is better than expected, the well can be choked back at the surface which will move the system curve into the safe region, of course with a loss of overall efficiency.



ESP – Pump

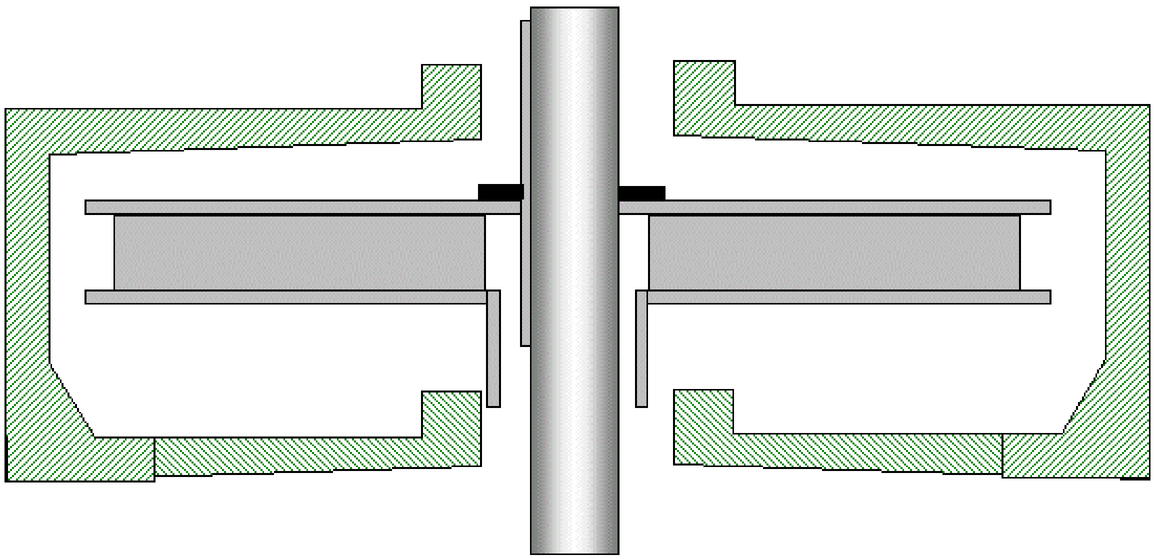
If a well's performance deteriorates to a certain point, the stages will go into downthrust. There is not much that can be done at this point but to prepare for replacement.



Some operators have re-circulated liquid from the wellhead into the casing annulus and thus back into the pump to increase the rate through the pump.

ESP – Pump

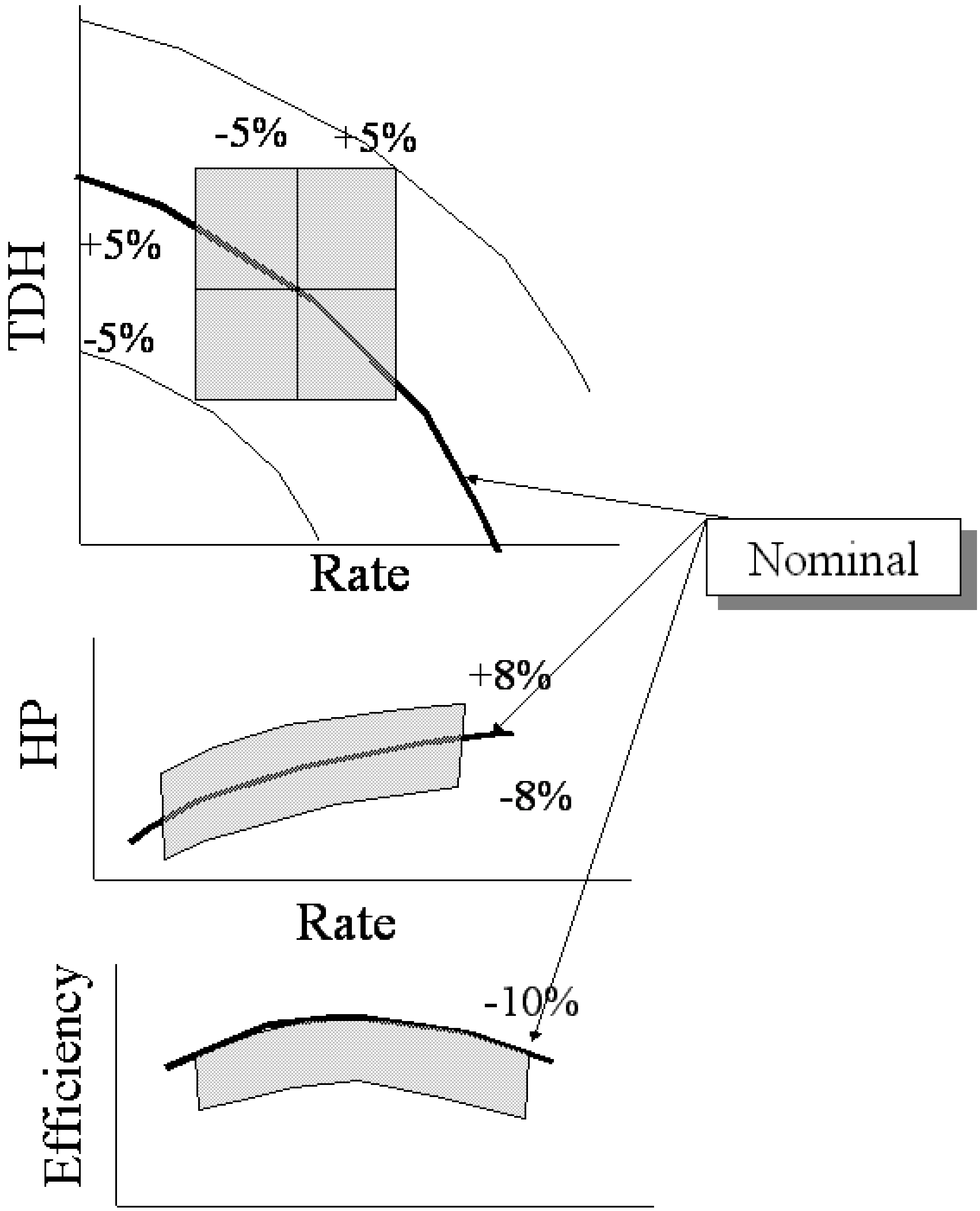
The range restrictions apply to mainly to floaters. Some pumps have the impellers fixed to the shaft in the vertical direction. These are called ***compression pumps***. Some pumps have a mix of compression and floating stages.



Compression pumps transmit all of the pump forces to the bottom of the shaft which creates a high thrust bearing load on the equalizer. Also, because manufacturing tolerances accumulate along the length of the pump, the number of consecutive compression stages is limited. Vendors continue to make progress in this area.

ESP – Pump

Be aware that any pump from a vendor's catalog is required by the API to perform within a certain range, perhaps worse than stated.



ESP – Pump

Once you know the basic performance of a pump, equations can be used to determine how rate, head and horsepower relate. These are the ***affinity laws***.

- $Q_2=Q_1(N_2/N_1)\ (D_2/D_1)$

The flowrate (Q) increases proportionally to the speed of rotation (N) and to the diameter of the impellers (D)

- $H_2=H_1(N_2/N_1)^2\ (D_2/D_1)^2$

The head (H) increases at the square of the speed of rotation (N) and at the square of the diameter of the impellers (D)

- $P_2=P_1(N_2/N_1)^3\ (D_2/D_1)^3\ \rho_2/\ \rho_1$

The horsepower required (H) increases at the cube of the speed of rotation (N) and at the cube of the diameter of the impellers (D) and proportionally to the density (ρ).

ESP – Pump

For a given pump, if you want to double the flowrate, you would expect to have to double the speed of rotation.

$Q_2=Q_1(2/1)$

If you double the speed of rotation, you will need eight times the horse power.

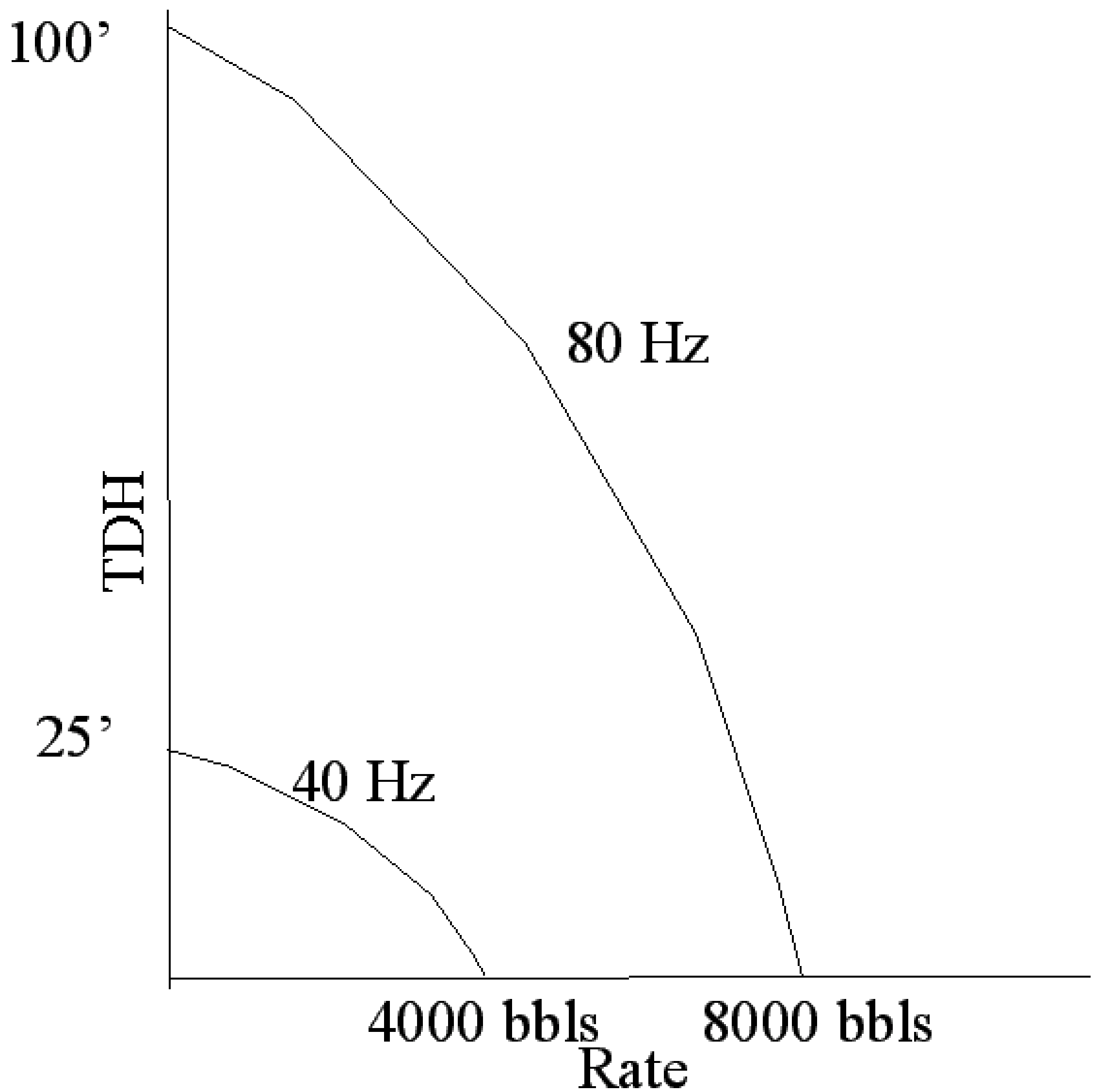
$P_2=P_1(2/1)^3=P_1(8)$

And the head generated by the pump would be four times as much.

$H_2=H_1(2/1)^2=H_1(4)$

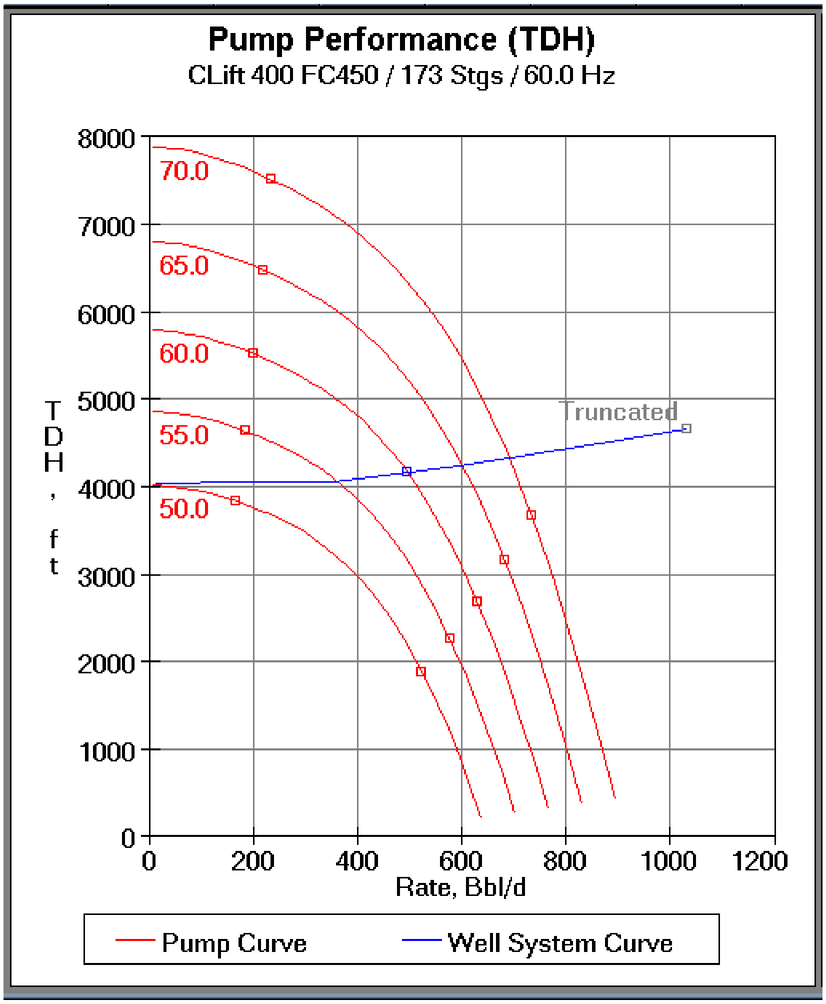
ESP – Pump

You can see the relationship between head and rate at various speeds of rotation in the ***variable frequency*** curves in the vendor catalogs.



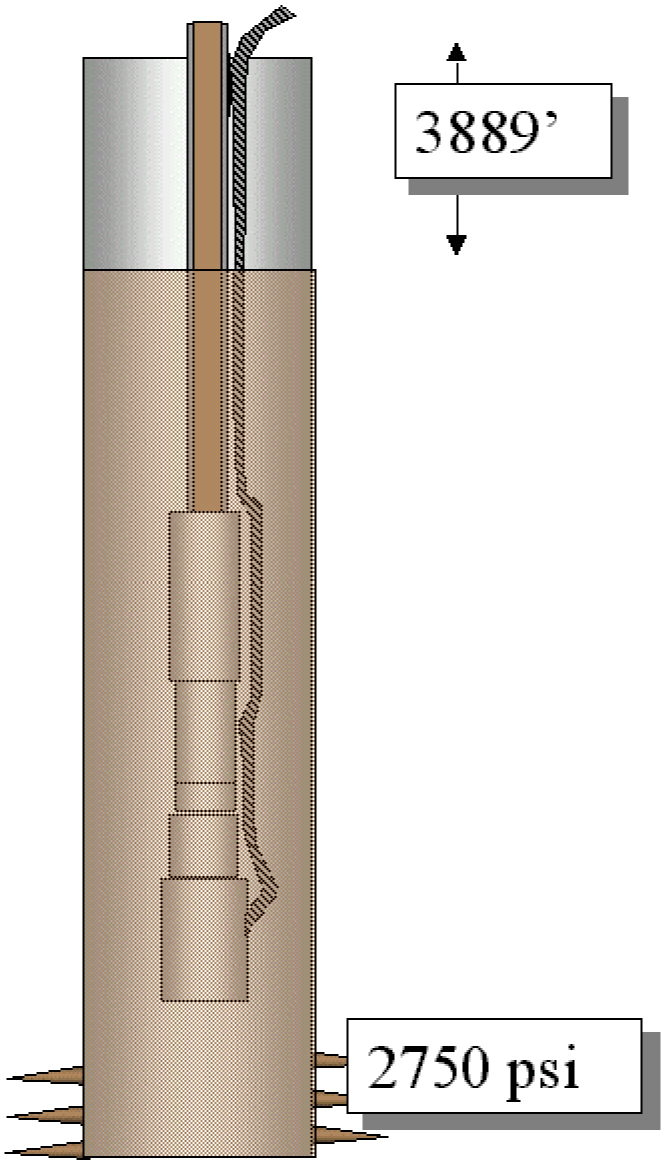
ESP – Pump

Here are the performance curves for the pump in SMI-130 A-7 at various frequencies:



ESP – Pump

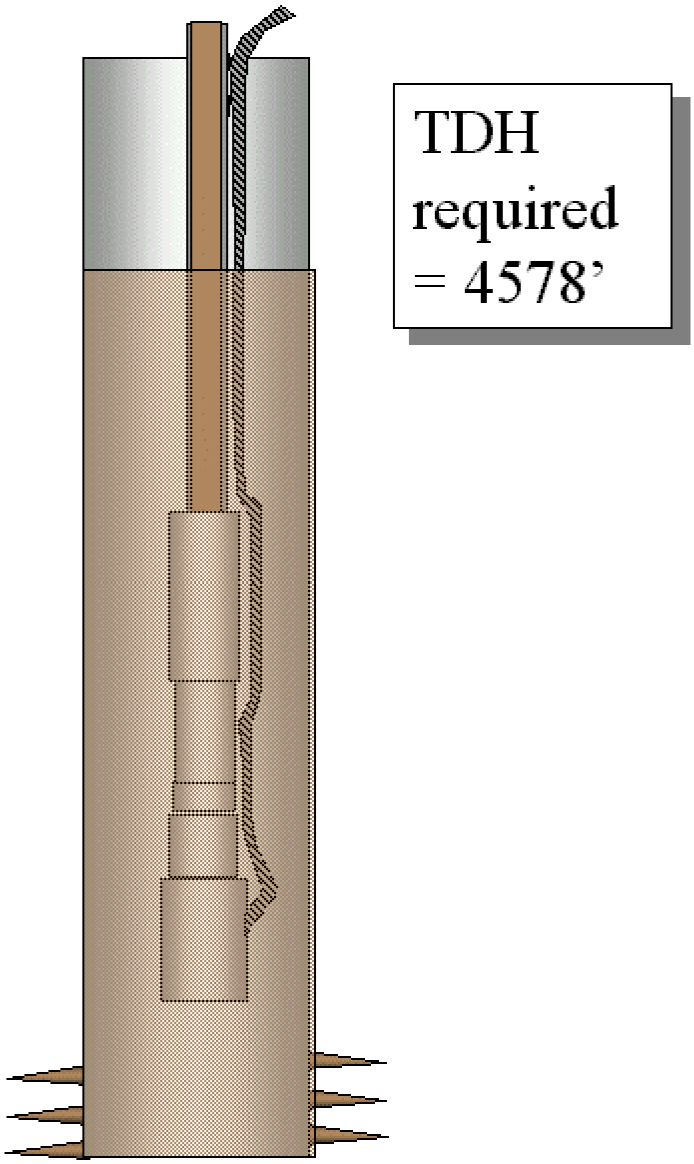
Take a simple case and see what is required of the pump.



This well has a SBHP = 3000 psi, a PI of 2 and is producing 500 bbl/d.
The FBHP = 3000 - 500/2 = 2750 psi
If the fluid in the well is at .45 psi/ft, the reservoir can support 2750/.45 = 6111' of liquid.
If the well is 10000' deep, the fluid level is 10000-6111=3889'.
This is the amount of head that the pump must supply just to lift the liquid to the surface at zero flowrate and atmospheric pressure.

ESP – Pump

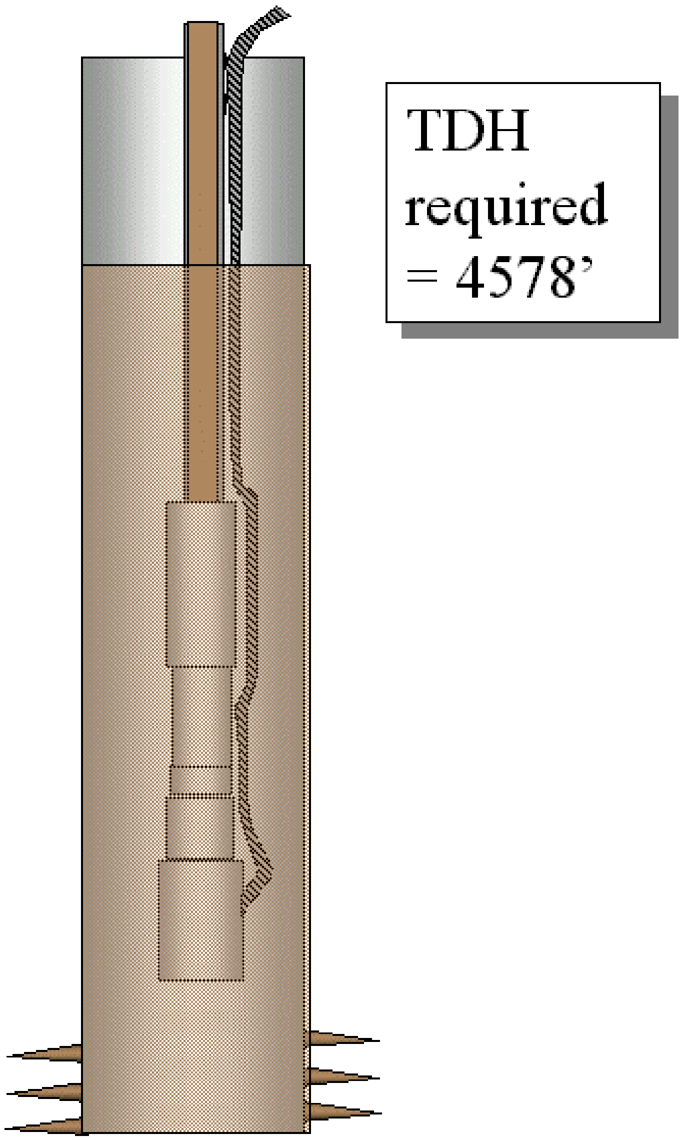
We have to pump the liquid into some sort of production system and through the tubing, so add the head required for this.



If the FTP=110 psi, add 110/.45 = 245'
If the friction in the tubing at 500 bbl/d is 200 psi, then add 200/.45= 444'.
The total head the pump needs to develop is 3889+245+444=4578'.

ESP – Pump

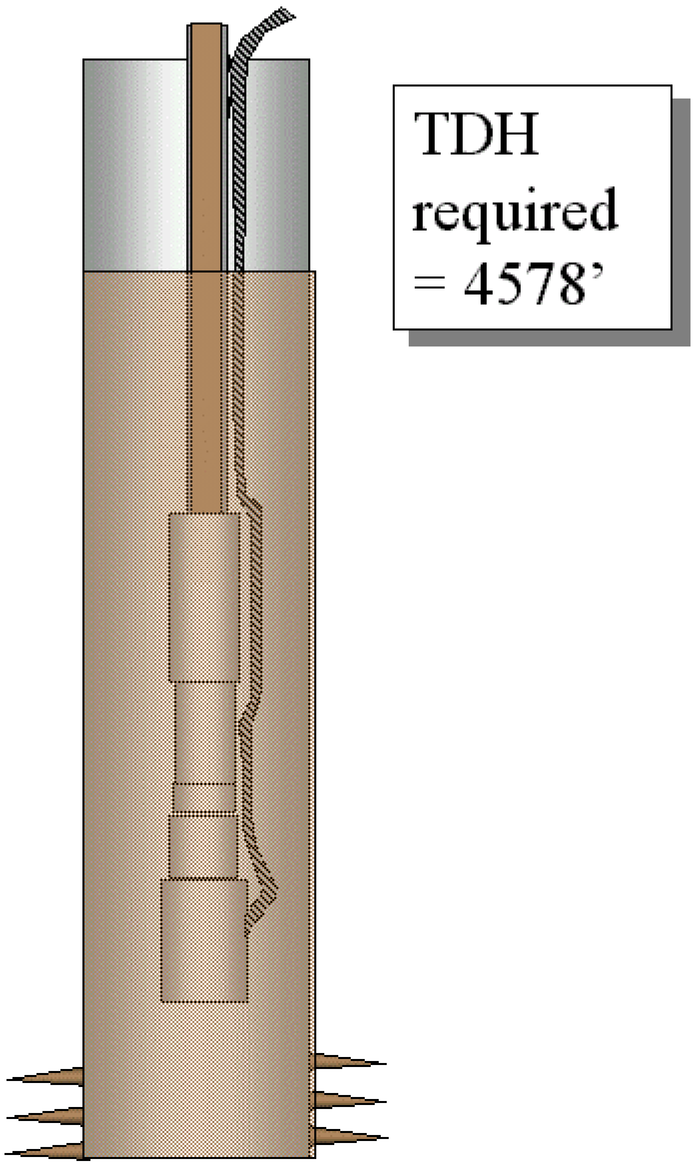
To calculate the horsepower, we need to know the specific gravity and the efficiency of the pump.



The horsepower required by the pump can be found by:
BHP = rate (head) SG/(135771 Efficiency)
Since the gradient of fresh water is .433 psi/ft, our fluid has a SG= .45/.433 = 1.04
If the efficiency is 60%,
BHP= 500*4578*1.04 / (135771*.6)
= 29.2 HP.

ESP – Pump

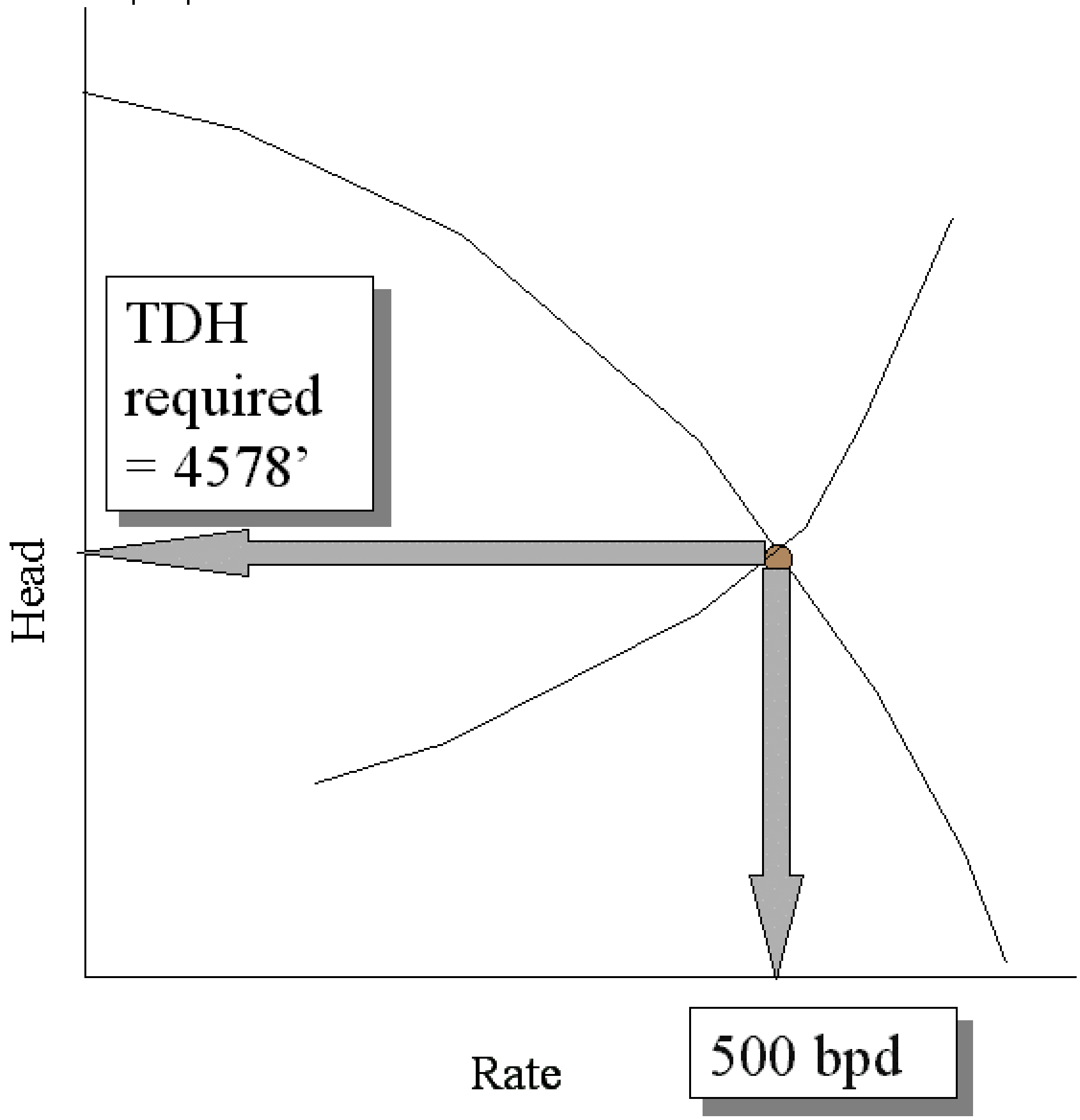
Since the impellers must be small enough to fit in a well, the head generated by each one is limited.



Assuming the head per stage were 32 feet (this varies ***widely*** with different pumps), the number of stages required would be 4578/32
= 142 stages.

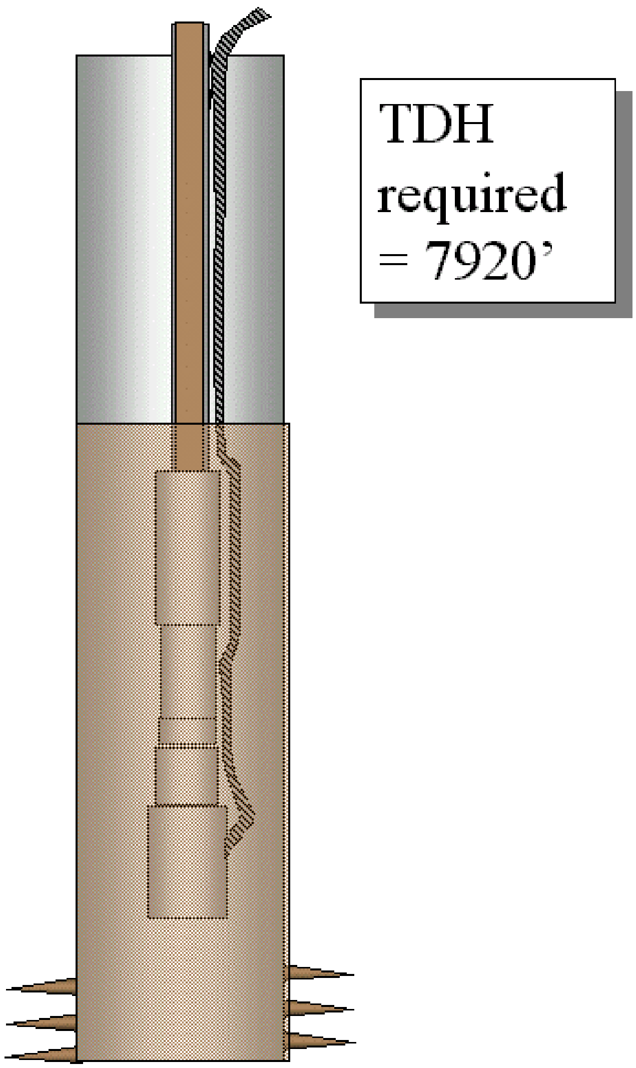
ESP – Pump

Here is the pump curve for this case:



ESP – Pump

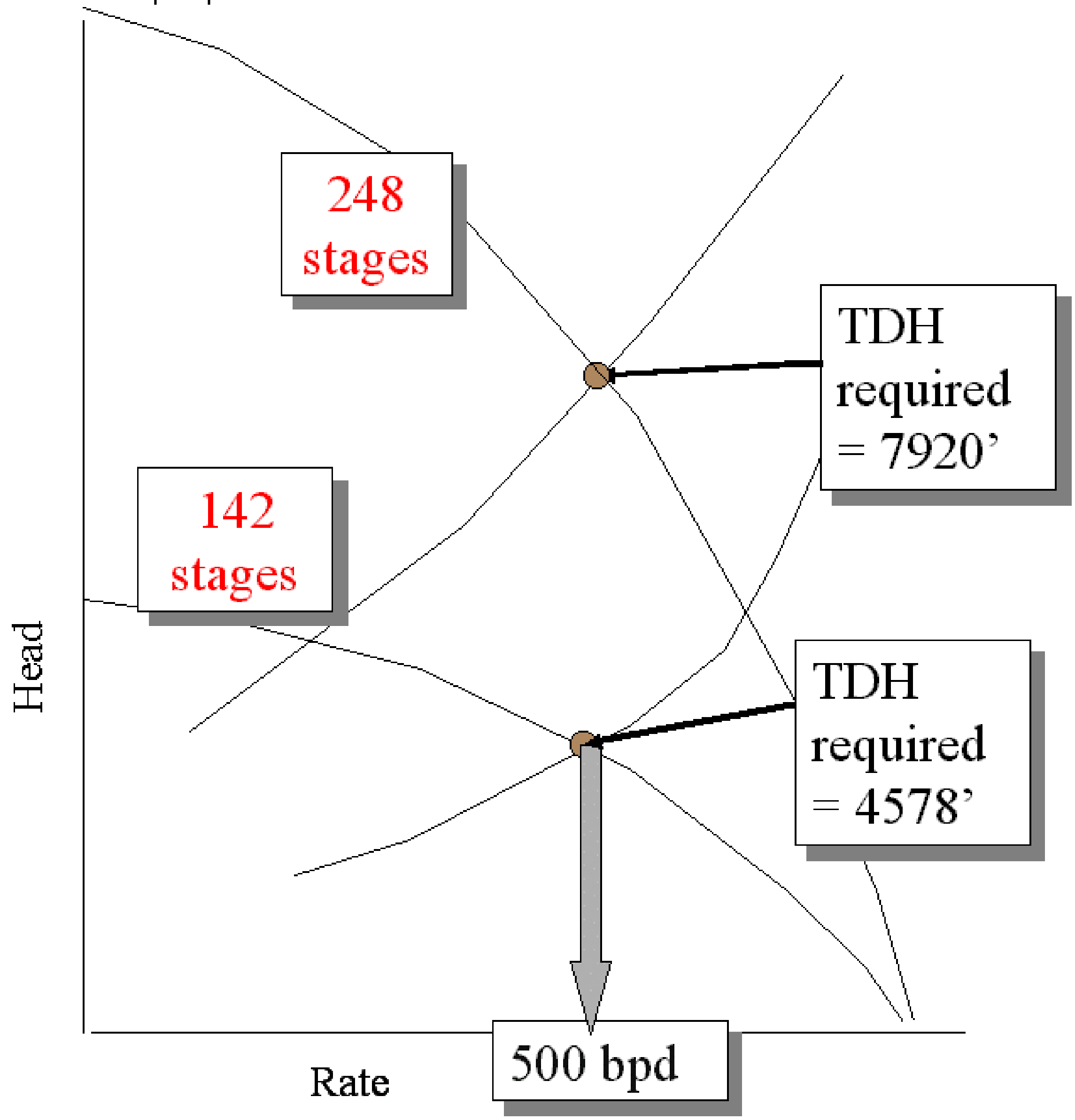
Let's repeat this for a lower SBHP, later in the well's life.



SBHP=1500
PI=2, so FBHP= 1500 - 500/2=1250 psi
The resv can support
1250/.45 = 2778'
To lift to the surface requires 10000-2778=7222'.
Adding in the friction and FTP head gives
7222+245+444=7911'.
BHP=500*7911*1.04 / (135771*.6)=50.5 HP
And would require 7911/32=248 stages.

ESP – Pump

Here are the pump curves for both of these cases:

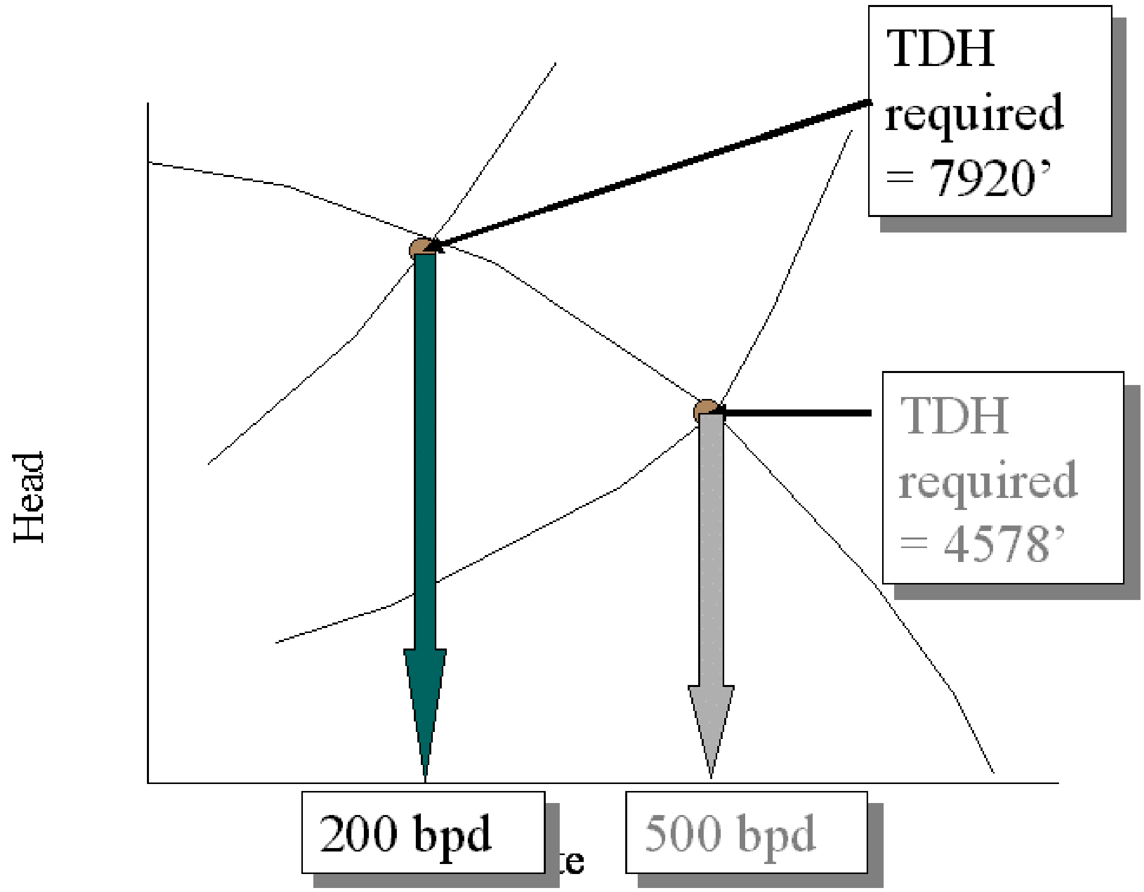


We might install a pump with more stages later in life.

ESP – Pump

On the other hand, the pump with 142 stages would not be able to make the same rate (assuming the same rotational speed) if we left it in the well.

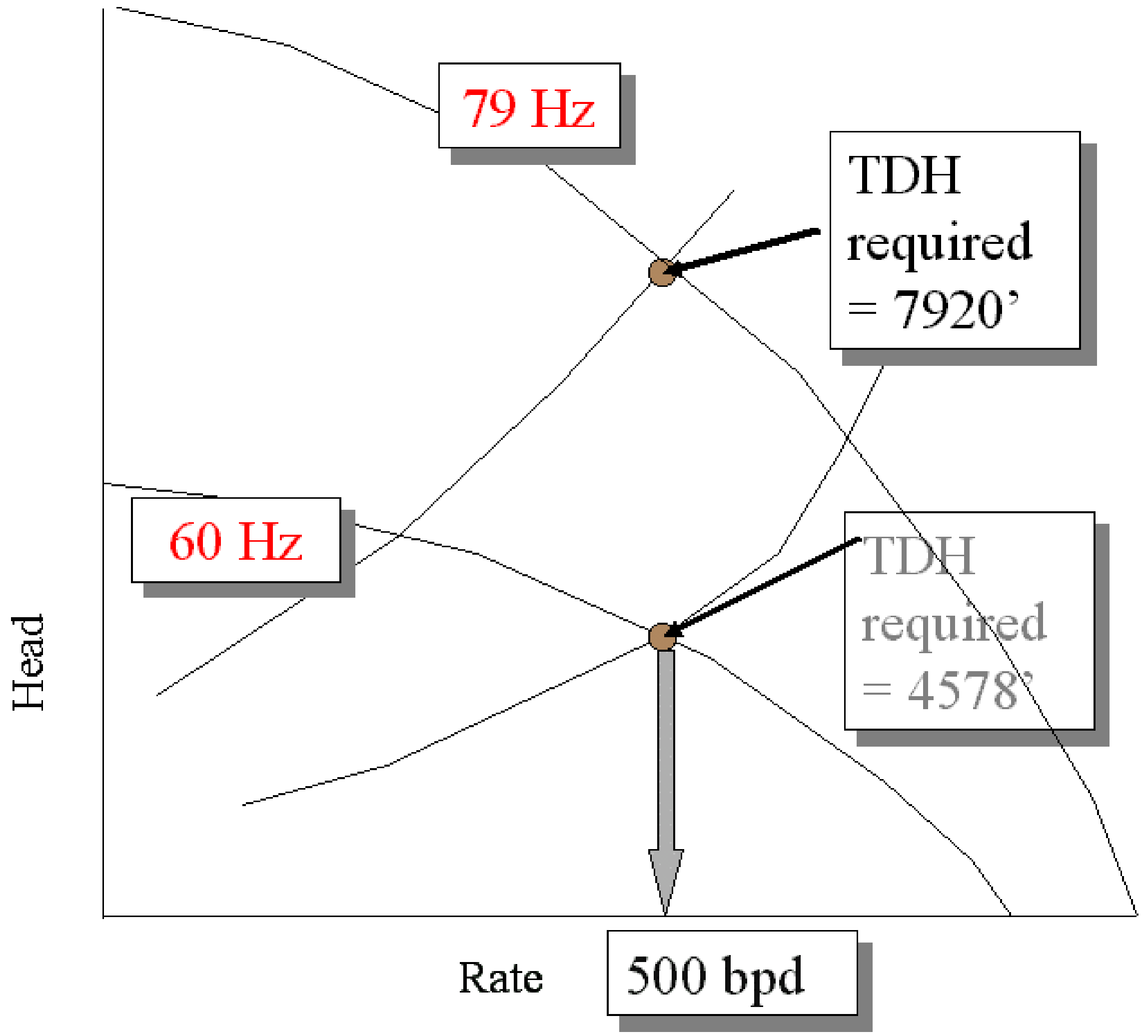
To find the rate, we need to first know the pump curve:



Because the rate is lower, the horsepower required is also much less:
BHP=200*7920*1.04 / (135771*.6)=20 HP
but similar to the initial case.

ESP – Pump

There is another possibility. If we want to make 500 bpd with the 7920' head, we might be able to choose another rotational speed.



If $H_2/H_1 = (N_2/N_1)^2$ then $N_2 = N_1 (H_2/H_1)^{.5}$
so, assuming the base case was 60 Hz, the new speed would be:
$60 * (7920/4578)^{.5} = 79$ Hz

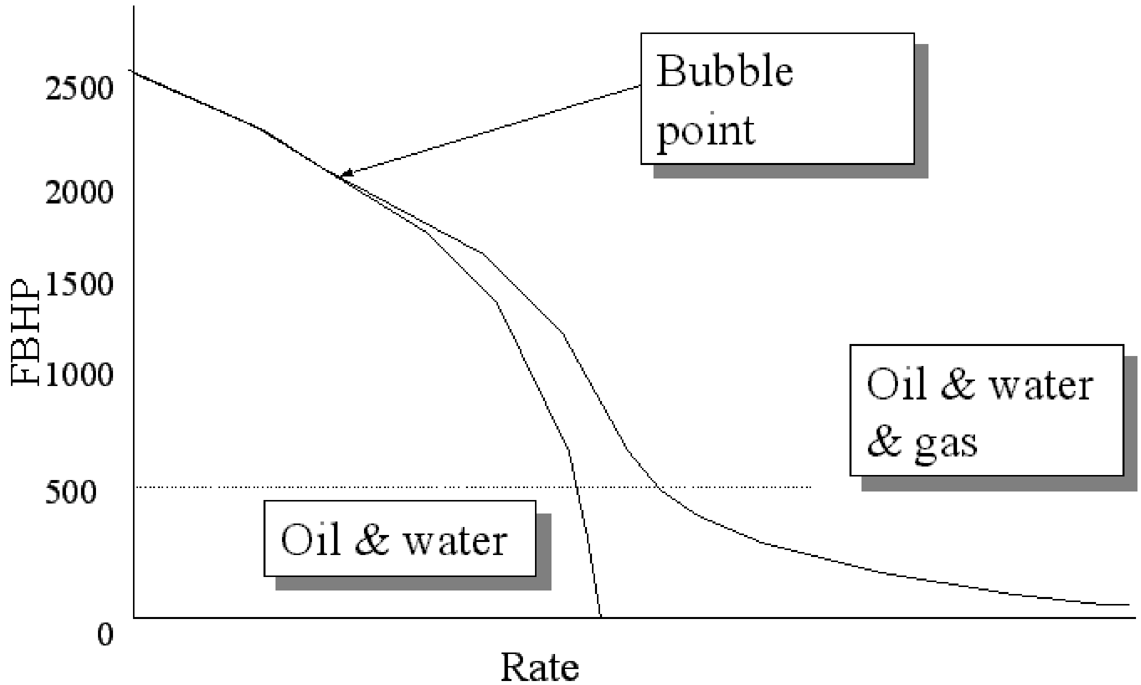
The horsepower required is:
BHP=500*7920*1.04 / (135771*.6)=50.6 HP

To change the rotational speed we need a ***variable speed drive, VSD***.

5 ESP - Pump Intake

What to do about gas?

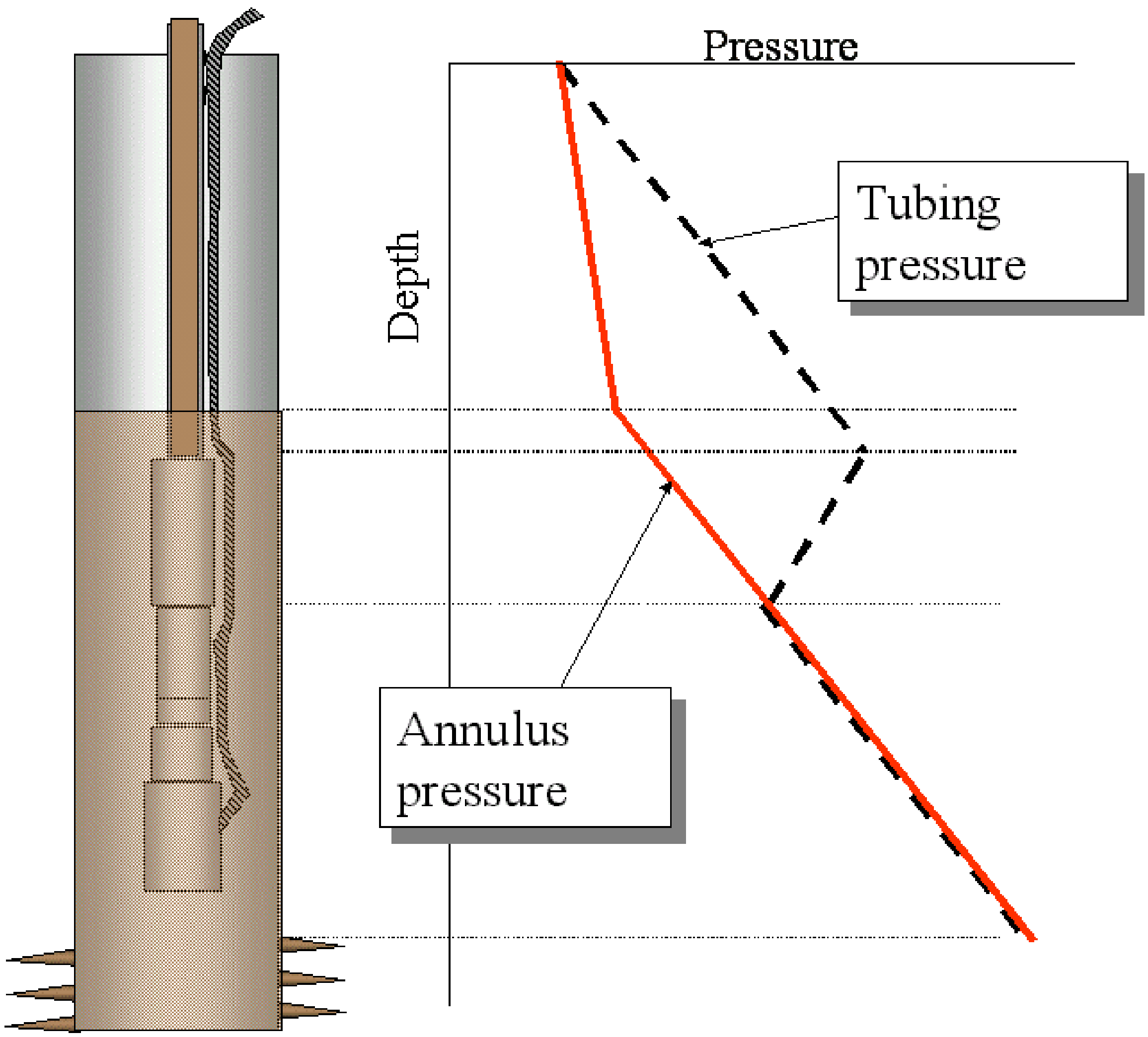
We already know that pumps don't like gas. But how much is too much? This is one of the most researched items in the recent development of ESPs.
Why is gas bad? We will discuss gas locking later, but one problem with gas is it takes up space in the pump we need for pumping liquids.
The gas volume increases rapidly especially below ~500 psi.



ESP - Pump Intake

What to do about gas?

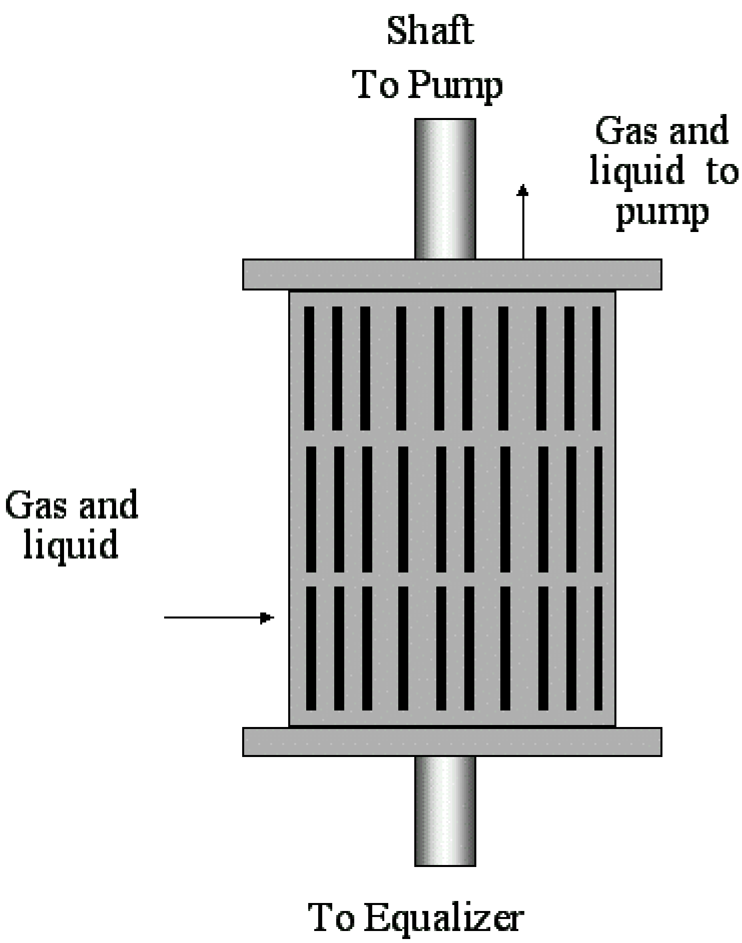
So if we don't want gas in the pump, where does it go? In a normal installation without a packer, gas is allowed to go up the annulus. The very low gradient for gas means that for a given FBHP, the gas can still have enough pressure at the surface to flow into the flowline with the pumped fluids.



ESP - Pump Intake

What to do about gas?

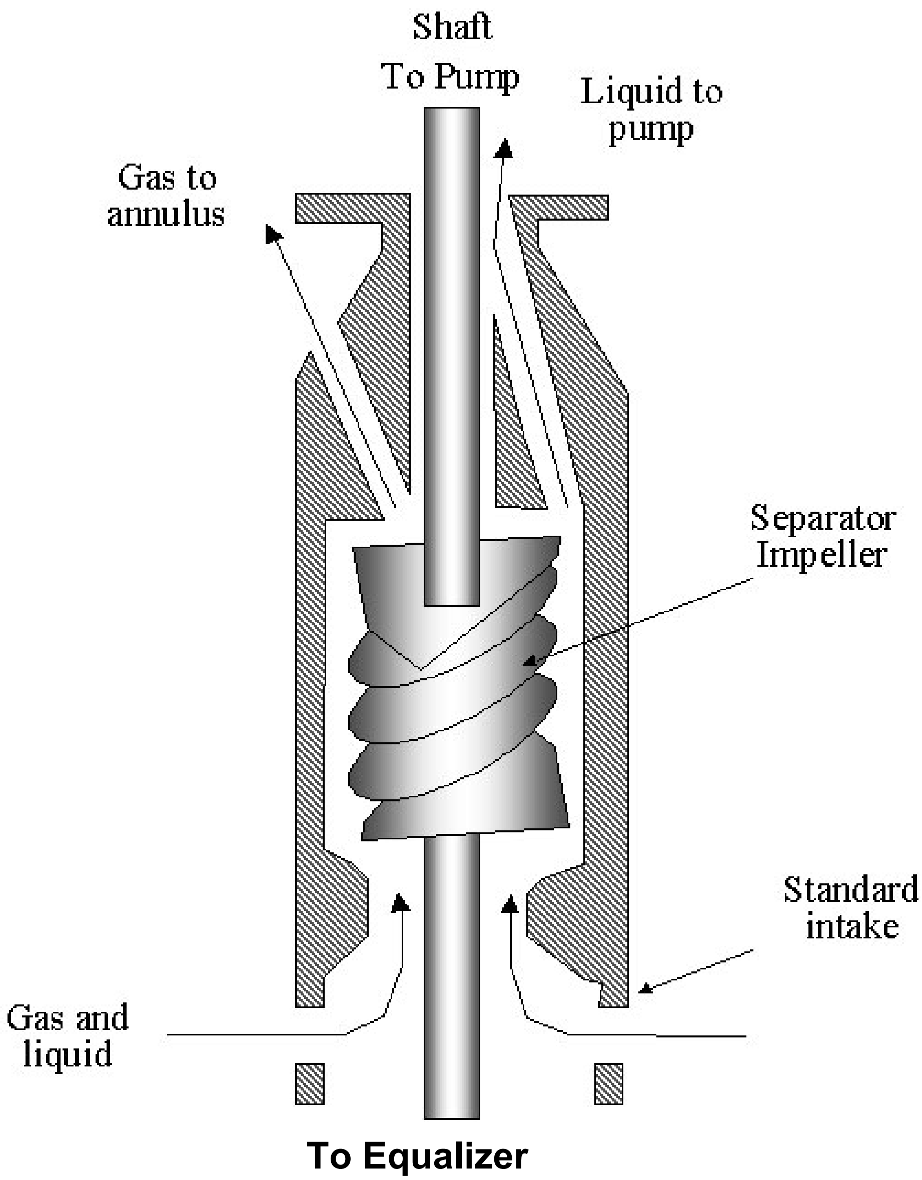
The fluids are taken into the pump through the ***pump intake***. A ***standard intake*** has a coarse screen to keep out large debris.



ESP - Pump Intake

What to do about gas?

We can minimize gas into the pump by trying to force it into the annulus. We do this by modifying the pump intake to include a ***centrifugal separator***.



ESP - Pump Intake

Estimates for gas separation efficiency:

Natural separation without a separator 0%
With a shroud/reverse flow (static) separator 0-50%
Rotary Separator 40-80%

ESP - Pump Intake

What to do about gas?

The goal is to keep the gas volume fraction into the pump to less than 10%. This is conservative and at higher pump intake pressures the pump can handle 40%+ gas, although the gas still takes up volume required for liquid.

The free gas fraction at the pump is calculated by SubPump or can be calculated by

FGF = Qg / [Qg + Qo + Qw]

Qg = free gas rate at pump = qo(GORresv - GORpump)Bg

where q_o = oil rate at surface conditions (bopd)

GORresv = solution GOR of oil at reservoir conditions

GORpump = solution GOR at pump intake conditions

B_g = Formation Volume Factor for gas (rb/scf)

Qo = $q_o(B_o)$

Qw = q_w, where q_w = water rate at surface conditions (bwpd)

For gas into the pump, include the separation efficiency:

FGFpump = Qg*(1-eff) / [Qg*(1-eff) + Qo + Qw]

where eff=separation efficiency

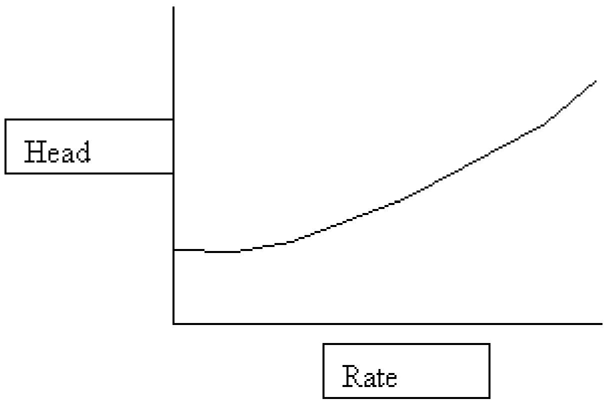
ESP - Pump Intake

What to do about gas?

For a typical situation:
500 bopd
wc= water cut = 30%
GORresv = 544 scf/bbl
GORpump = 532 scf/bbl
Bo = 1.2 rb/bbl
Bg = .00295 rb/scf
So, Qo = 500*1.2 = 600 rb/d
Qw = 500 * (wc / (1-wc)) = 214 rb/d
Qg = 500(544- 532).00295 = 17.7 rb/d
FGF = Qg / [Qg + Qo + Qw]
=17.7 / (17.7 + 600 + 214) = .021, or 2.1%

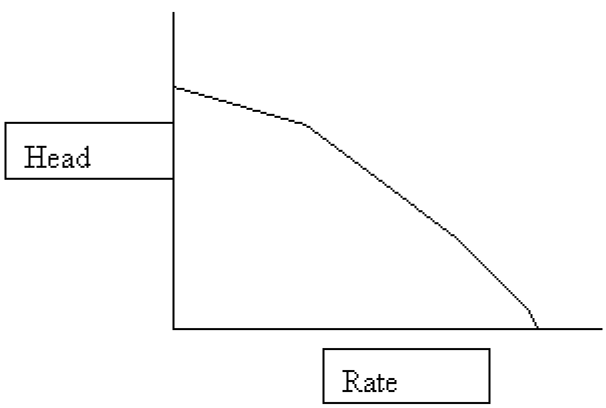
For reference:
Bg = 1/(5.615E) where E = 35.37 p / (ZT)
If BHT = 200F, then T=(200+460) = 660 R
Z = 0.9 and p = 1014 psia, then E = 60.37
and Bg = .00295 rb/scf

5.1 ESP Pump Questions



What is the curve above called?

What does it represent?



What is the curve above called?

What does it represent?

ESP Pump Questions

The pump curve shows that
a. as the head increases the rate increases
b. as the rate increases the head decreases
c. as the rate decreases the head decreases
d. as you get older the more similar these answers seem

An ESP is a _____ pump.
a. reciprocating
b. centrifugal
c. turbine

The intersection of the system curve with the pump curve is the _____ rate from the system.

The pump curves in vendor catalogs are developed by:
a.calculations based on experimental work
b. .testing with kerosene
c. .testing with water
d. .correlations

How many feet of head is generated by an ESP pumping 250 bbl/d of a 0.5 psi/ft brine from a zone 5000' deep to the surface at 0 psig through 8" casing? Assume the intake pressure at the pump is near zero.

How many feet of head if the SG of the fluid were 2.0?

How many feet of head if the well were 10000' deep and the SG=.73?

What is the outlet pressure of an ESP pumping 250 bbl/d of a 0.5 psi/ft brine from a zone 5000' deep to the surface at 0 psig through 8" casing?

Most impellers in ESPs are:
a. axial
b. mixed
c. radial

How many stages does a typical ESP have?
a. 3-5
b. hundreds
c. thousands

ESP Pump Questions

Most ESPs contain:
a. compression stages
b. floating stages
c. components too complex for most of us to understand

Choose an operating point for your pump:
a.strong upthrust
b.strong downthrust
c.light upthrust
d.light downthrust
Why?

Downthrust occurs at
a.Low rates
b.High rates
Why?

If the ESP is in upthrust, you can cure this by:
a. choking the well back
b. recirculating fluid from the flowline to the casing

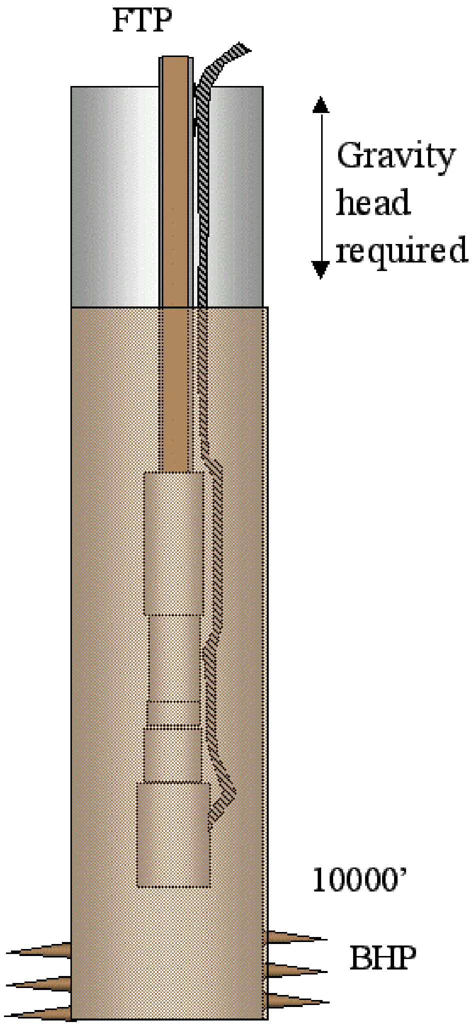
If I want to quadruple the head from an ESP, I need to
a. triple the rate
b. double the horsepower
c. double the speed

Gas in an ESP is more of a problem at:
a. high rates
b. high pressures
c. low pressures

In a typical ESP well, most of the gas from the reservoir goes _______ to reach the surface.
a. through the tubing
b. through the casing
c. through the cable

For a well with 4% gas at the pump intake
a. get a gas separator installed as soon as practical
b. get a gas separator installed if the well is worked over
c. no need to install a gas separator on this well

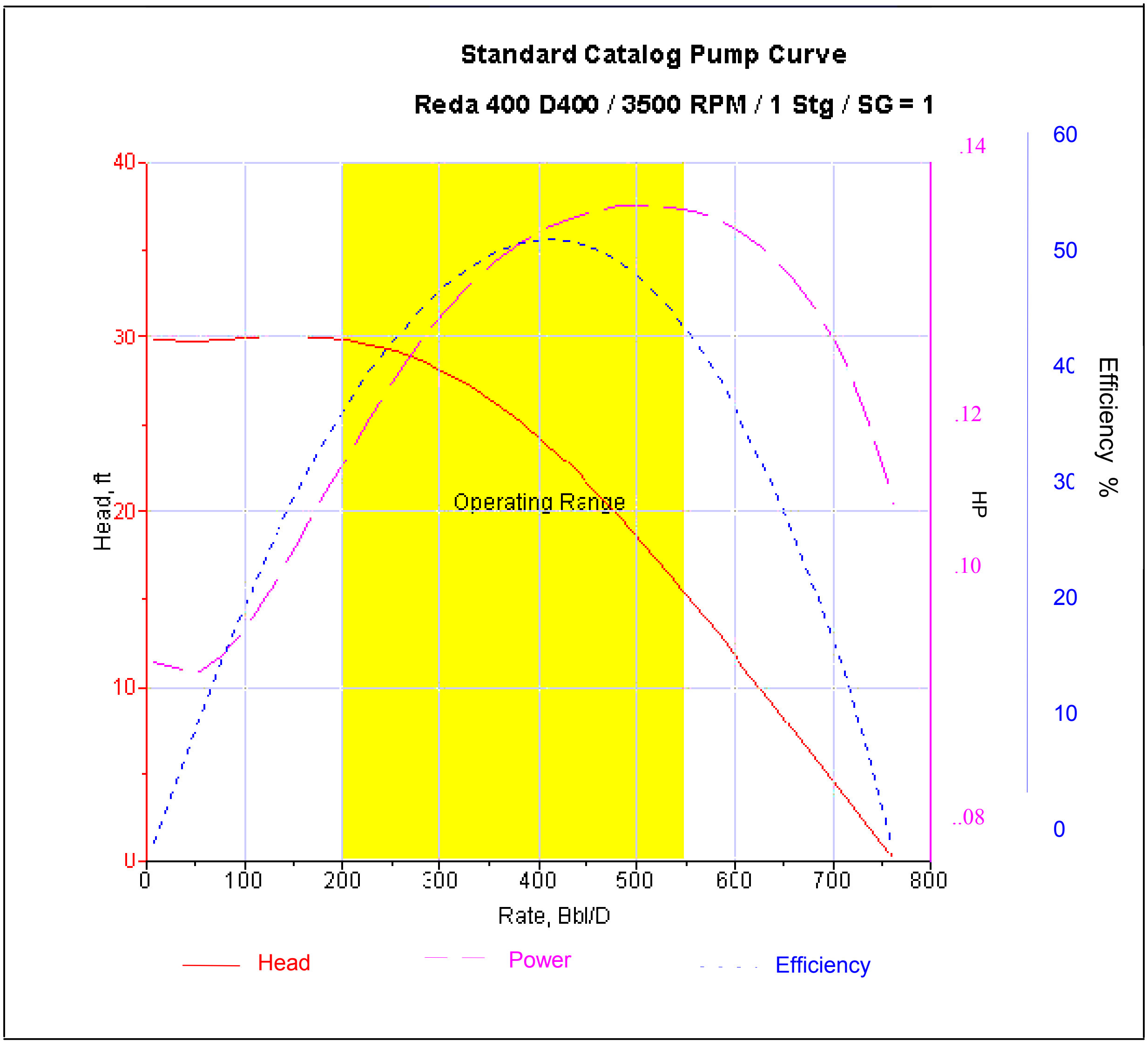
5.2 ESP - Pump Problem



Given:

SBHP = 3000 psi
Q = 500 bbls/d
PI = 2 bbl/d/psi
Depth of pump/perfs = 10000'
Gradient of fluid is 0.441 psi/ft
FTP = 110 psi
Friction drop in tubing = 3 psi
Assume Bo (FVF) = 1
Pump curve for D400 next page.

ESP - Pump Problem



ESP - Pump Problem

Calculate:

• FBHP

• Gravity head required

• Discharge pressure required

• TDH required

• BHP required

• Number of Stages

Future case

Given SBHP = 1500 psi

What are the expected operating conditions and recommendations?

5.3 ESP - Pump Intake Problem

Given:

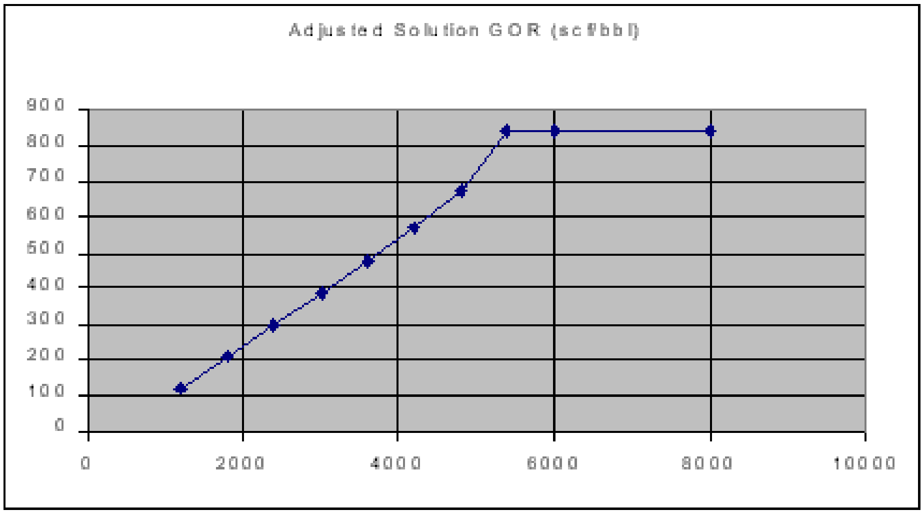
Pump intake pressure = 2400 psi and
Bo, Bg -- see graphs on next page

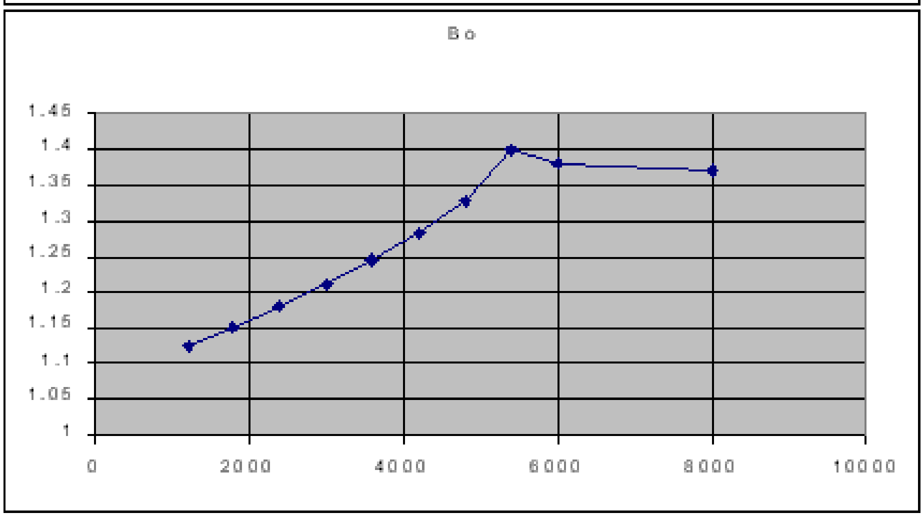
What is the gas fraction going into the intake?

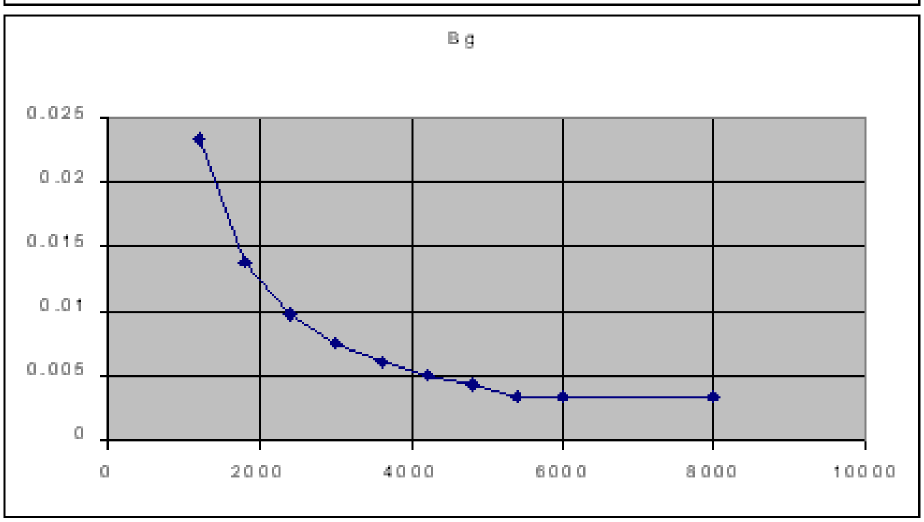
What is the gas fraction going into the pump if the gas separator is 60% efficient

What separation efficiency would be necessary to achieve a free gas fraction into the pump of 15%?

Is the gas fraction into the pump going to be a problem in this environment?


Adjusted Solution GOR (scf/bbl)
900
800
700
600
500
400
300
200
100
0
0
2000
4000
6000
8000
10000

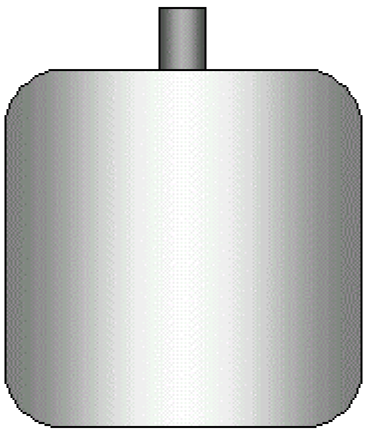

Bo
1.45
1.4
1.35
1.3
1.25
1.2
1.15
1.1
1.05
1
0
2000
4000
6000
8000
10000


Bg
0.025
0.02
0.015
0.01
0.005
0
0
2000
4000
6000
8000
10000

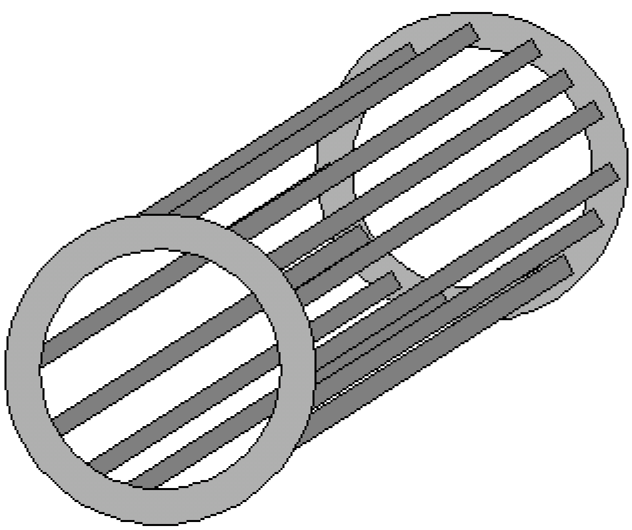
6 ESP – Motor

The ESP motor is not designed like an ordinary motor.

If you look at a typical motor it looks like this.
This is a very efficient shape, electrically and for manufacturing.

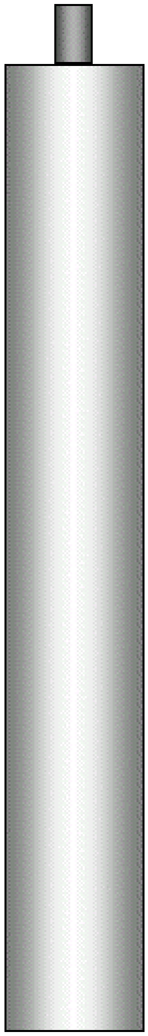


A common type of motor is the three phase, squirrel cage type motor, so called because of the rotor appearance.



ESP – Motor

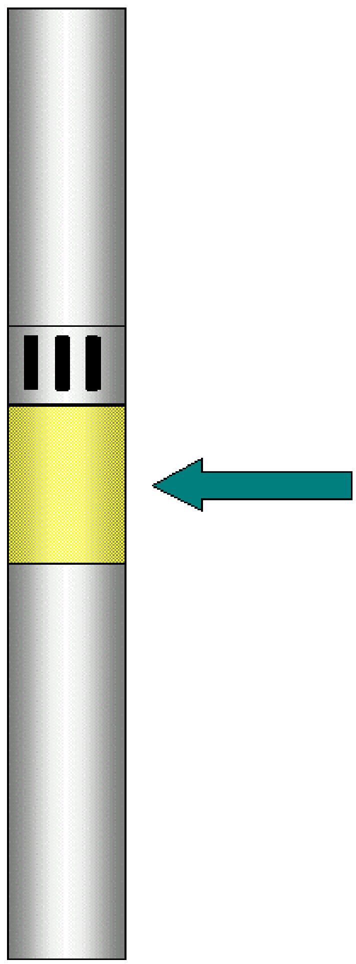
The ESP motor is not designed like an ordinary motor.



An ESP motor works on the same principles, but must fit into a long skinny wellbore.
This compromise means less efficiency, and thus greater heat buildup.
Also, normal motors have fans for cooling but the ESP motor has only the flow of well fluids to cool it.

7 ESP – Equalizer

This device sits between the pump intake section an the motor.



The equalizer (aka protector) has three primary functions:

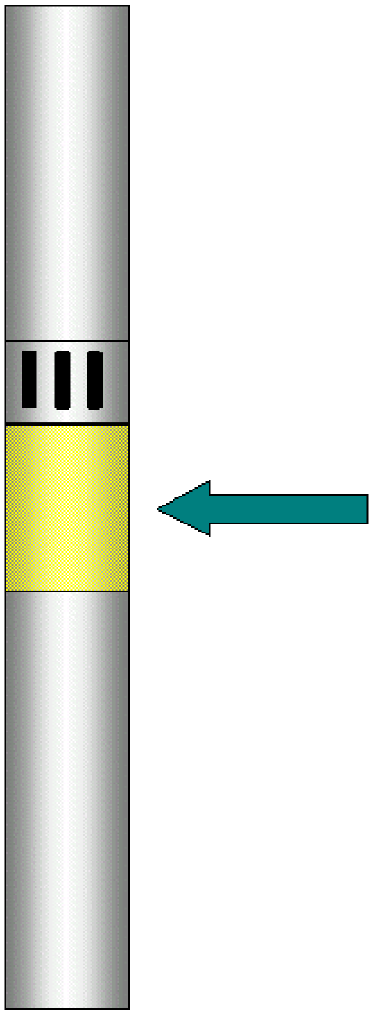
• keep well fluids out of the motor

• carry the upthrust or downthrust developed in the pump

• couple the torque developed in the motor to the pump

ESP – Equalizer

Why not just seal the motor?



An ESP motor undergoes tremendous changes in temperature during normal operation.

The motor is full of special non-conductive fluid which lubricates and electrically insulates the components.

The motor must be full of this fluid to operate properly.

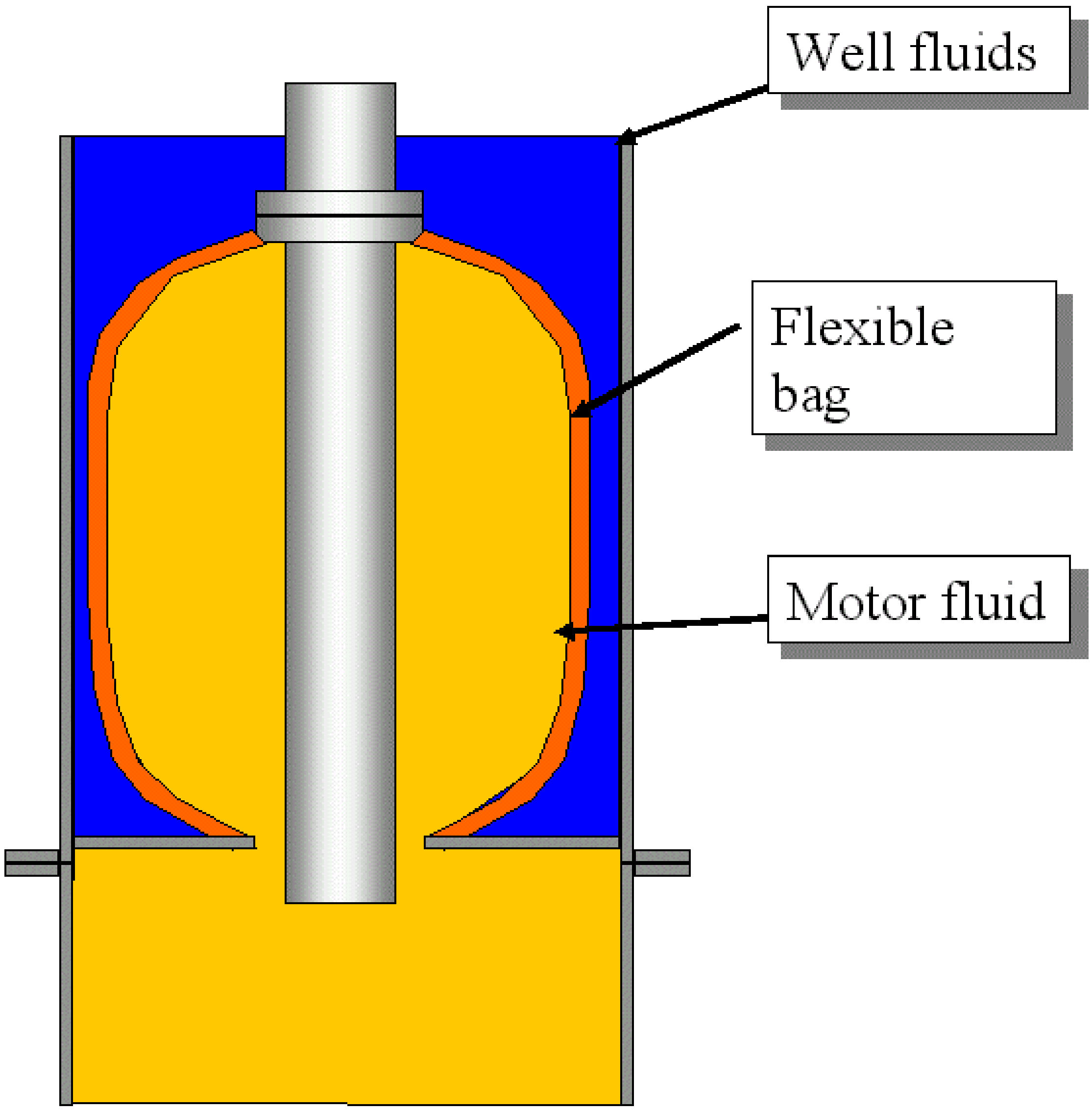
When the motor gets hot, this fluid needs to expand. The equalizer allows this expansion.

ESP – Equalizer

7.1 Types of Equalizers

There are two primary types of equalizers.

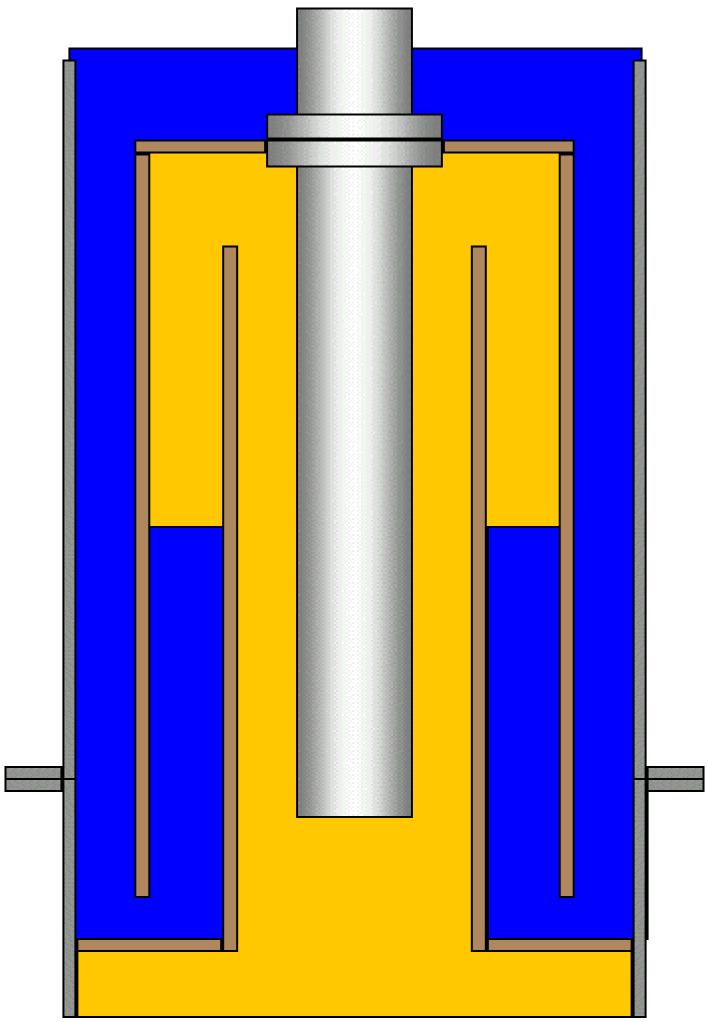
The bag type or positive seal protector uses a flexible bag to take the variation in motor fluid volume.



ESP – Equalizer

Types of equalizers

The other kind of equalizer is a labyrinth seal. It works by a u-tube principle and requires a significant difference in specific gravities between the motor and well fluid. Also it is not useful in deviated wells.



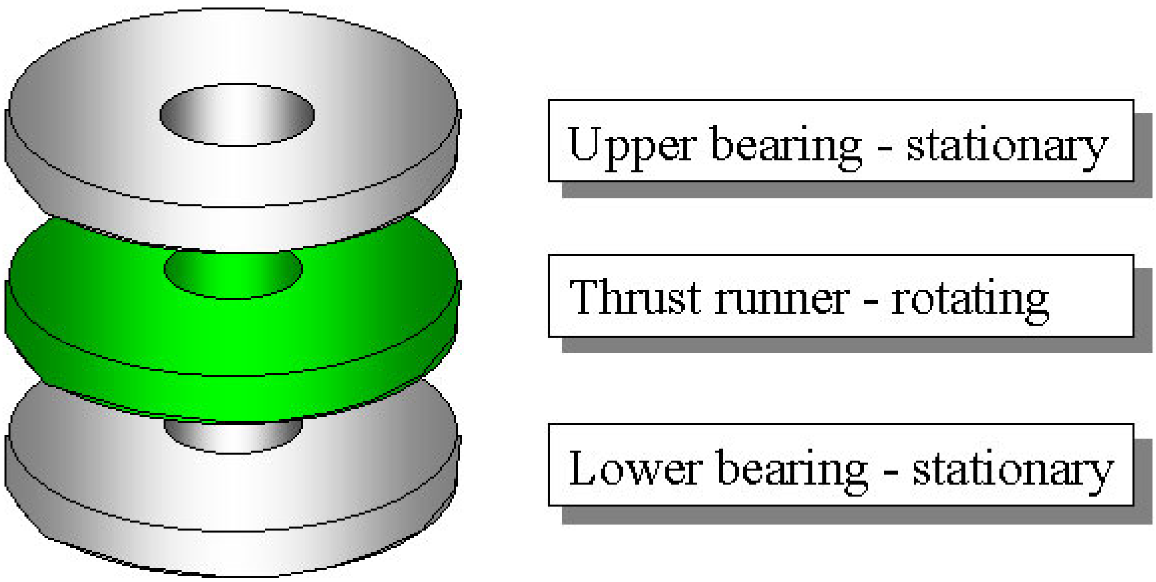
ESP – Equalizer

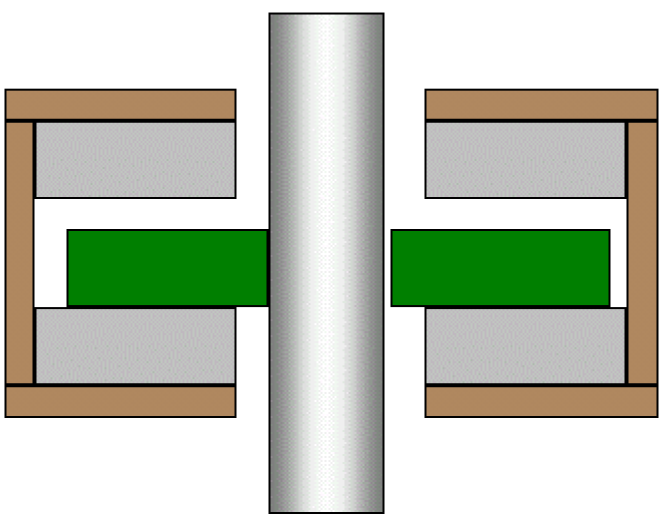
Types of equalizers

Many times both labyrinth and bag equalizers are used together.
However, bags may develop leaks. Also they may not last as long when in contact with the well fluids.
The labyrinth equalizer can't leak, but may be subject to gradual contamination as the well fluids move in and out of the seal. Contamination is more rapid if re-starts are common.
You can put two equalizers in series so that if one fails the other still isolates. Two in parallel can provide for more expansion.
A common configuration is to put a labyrinth seal above a bag. The labyrinth keeps the well fluids from contacting the bag.
Some ESPs have 4 or more seals with a combination of seals in parallel and in series.

7.2 Thrust Bearing

Aside from the seals, the equalizer must contain a section to carry the thrust from the pump.





7.3 ESP Motor & Equalizer Questions

The ESP motor is a:
A. two phase, squirrel-cage motor of high efficiency
B .three phase, squirrel-cage motor of high efficiency
C .three phase, squirrel-cage motor of low efficiency
D. single phase, hamster-cage motor of no efficiency

The ESP motor is cooled by
A .liquid from the surface
B. liquid from the formation
C. internal fans

The other name for the equalizer is __________.

Name the three things the equalizer does:

____
____
____

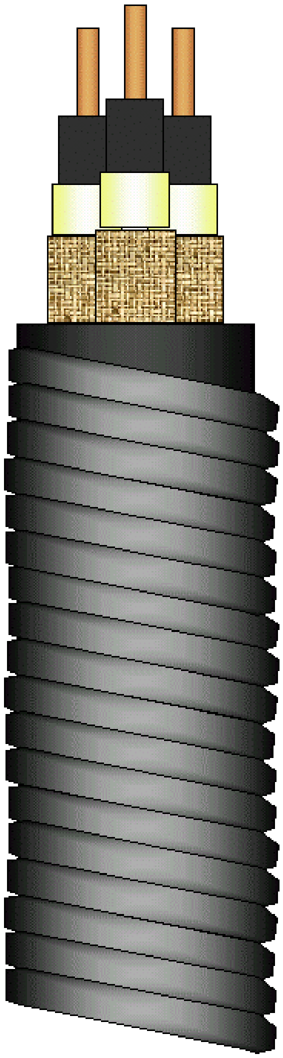
Name two kinds of equalizer assemblies

Which one is for high deviations?

What component of the equalizer takes the load generated by the pump shaft and impellers?

8 ESP – Cable

The cable is the largest and possibly the most expensive component of the ESP system.



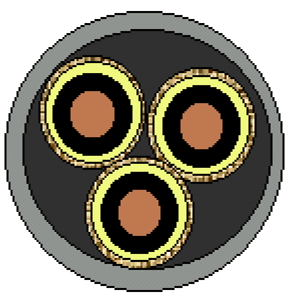
The ESP cable must carry the electrical power to the pump. It may also carry pressure and temperature signals back to the surface.

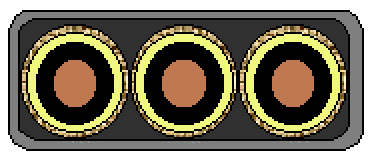
- Three copper conductors, one for each phase. These can be stranded or solid.
- A layer of electrical insulation.
- A layer of barrier tape to protect the electrical insulation from well fluids.
- A layer of braid to physically protect and contain all of the above around each conductor.
- A nitrile jacket enclosing the three insulated conductors.
- Metal armor to provide the main physical protection and give some extra tensile strength.
- Sometimes an expensive lead sheath is used to keep out H_2S gas.

ESP – Cable

The cable is the largest and sometimes the most expensive component of the ESP system.

All this complexity comes at a cost -- up to $50/ft.
Cables are rated in terms of conductor size, voltage and temperature rating.
The biggest challenge is (as the rest of the ESP system) keeping the OD as small as possible.
If this high voltage cable were going to be buried or run in a conduit on the surface, it would be several inches in diameter.
However, in a well it is restricted to about 1” OD.
This is still not small enough near the pump and motor (usually the largest ODs in the well) and flat cable must be used.
Flat cable has the conductors in parallel which provides less mechanical protection and more electrical losses.





ESP – Cable

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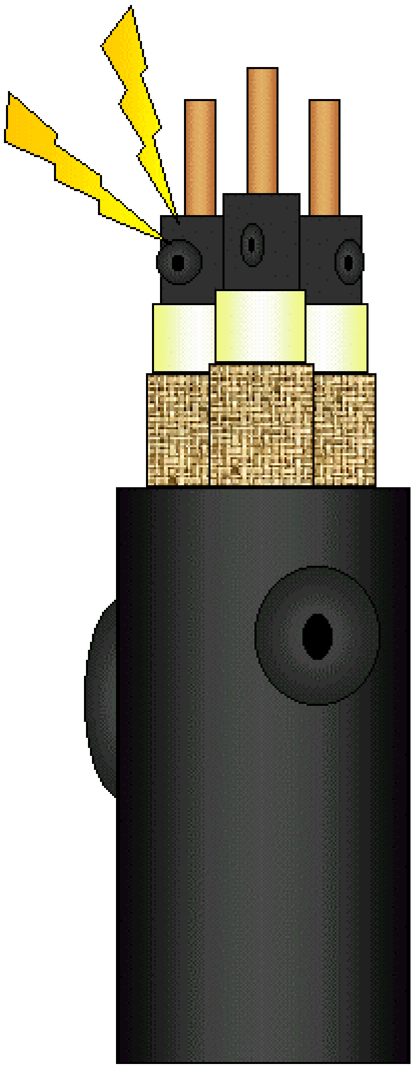


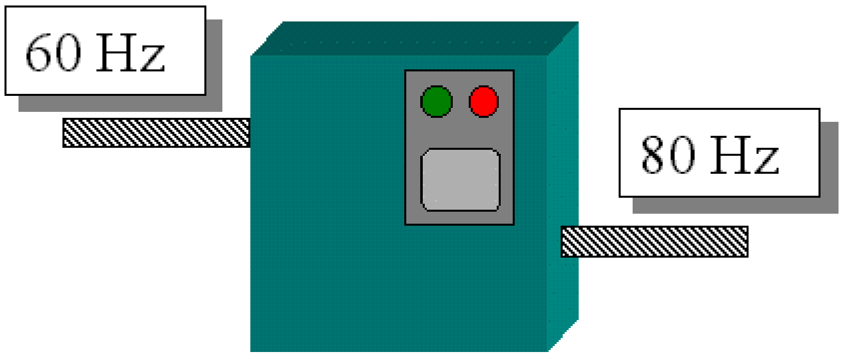
One problem with most cables is that gas (always present in the annulus) will eventually migrate slowly into the insulation of the cable.
Unless corrosive gases are present, this does not harm the cable.
However, if the pressure on the annulus is dropped quickly, the cable will suffer from decompression (just like a diver getting the bends).
Gas bubbles will expand and burst through the electrical insulation and the cable will short out.

Always depressure the annulus very slowly if at all.

9 ESP – VSD

The VSD gives flexibility to the otherwise fairly inflexible ESP system -- at a price.

The variable speed drive (aka variable speed controller, variable frequency controller, etc.) can change the rotational speed of the motor by changing the frequency of the AC power before sending it downhole to the ESP.



By changing the rotational speed of the pump, the operating range is greatly expanded.

ESP – VSD

The VSD gives flexibility to the otherwise fairly inflexible ESP system -- at a price.

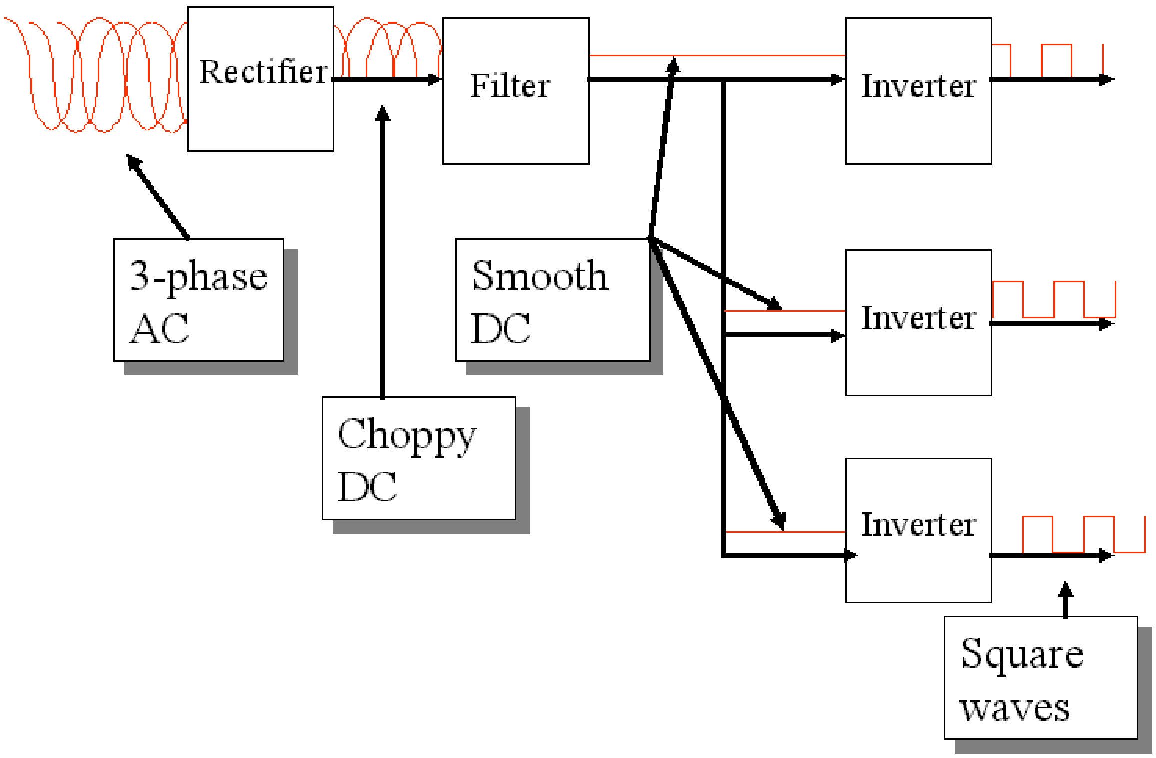
Here are some reasons to install a VSD:

- Produce the well to right to the limit of drawdown (sand, gas, water influx).
- Handle changing inflow performance (water flood response, pressure depletion, deteriorating PI, etc.)
- Keep power below power constraints.
- Operate smaller motors at higher horsepower.
- Test and produce at different rates.
- ‘Soft-start’ that reduces startup current is included.

ESP – VSD

The VSD gives flexibility to the otherwise fairly inflexible ESP system -- at a price.

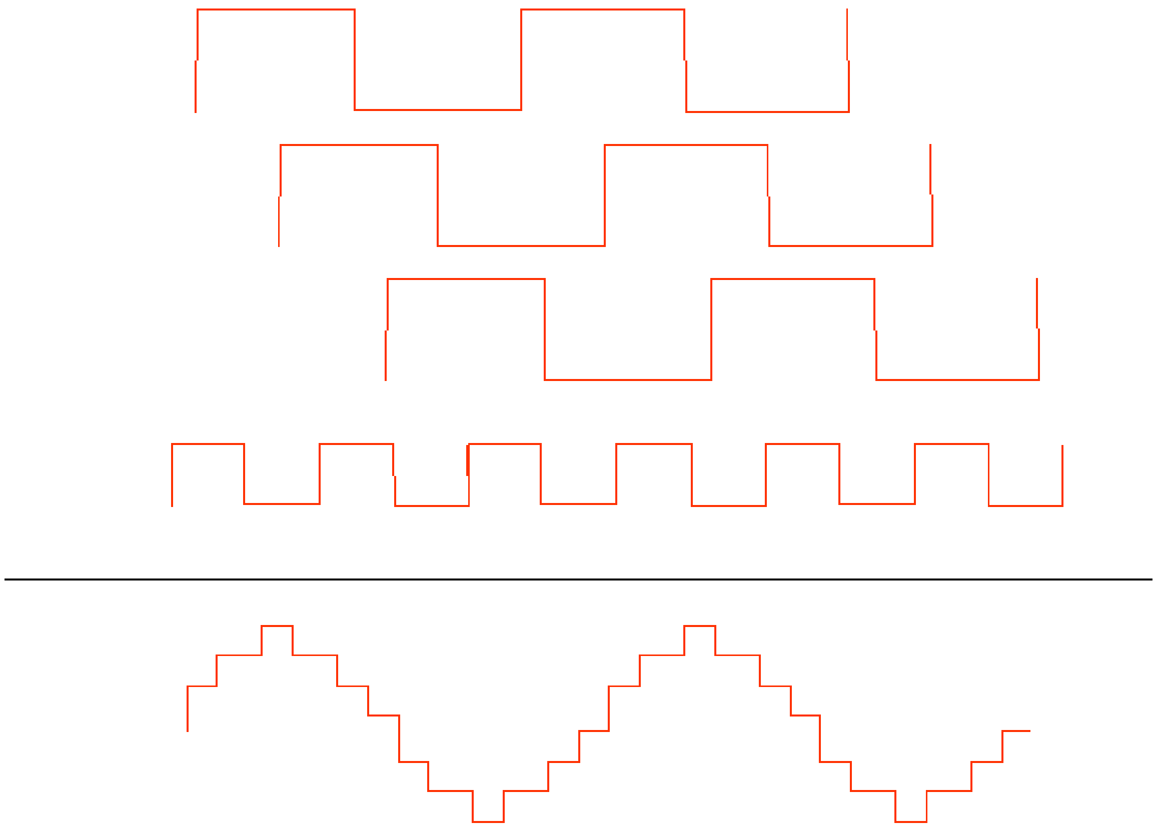
The VSD uses high voltage solid-state circuitry to convert the three phase AC into a set of square waves.



ESP – VSD

The VSD gives flexibility to the otherwise fairly inflexible ESP system -- at a price.

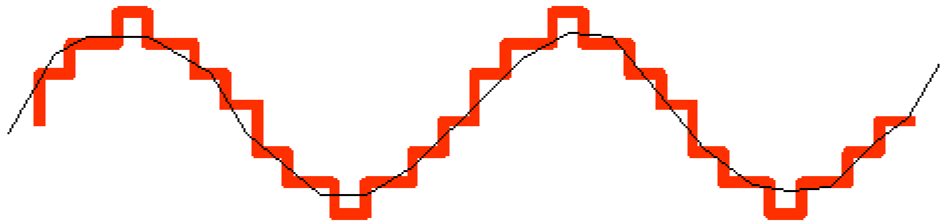
These square waves are added together to create a pseudo-sine wave for each phase.



ESP – VSD

The VSD gives flexibility to the otherwise fairly inflexible ESP system -- at a price.

The VSD can only approximate the perfect sine wave that the motor is expecting. The more steps the VSD is capable of producing, the closer the approximation and the more expensive the VSD.



Each point on the cycle where the voltage is higher or lower than the sine wave is energy that the motor cannot use which lowers the overall efficiency and generates excess heat.

ESP – VSD

The VSD gives flexibility to the otherwise fairly inflexible ESP system -- at a price.

All this high speed, high voltage circuitry

- has a substantial initial cost
- is sensitive and prone to failure
- creates additional heat in the motor

Because of these drawbacks, VSDs are not installed in most onshore applications.

However, they are more common in offshore applications where the replacement costs for re-sizing pumps are high and where cost is a smaller fraction of the total installation cost.

Sometimes VSDs are used following the initial completion to determine the performance characteristics of a well. Then this system is replaced with a properly sized fixed speed system.

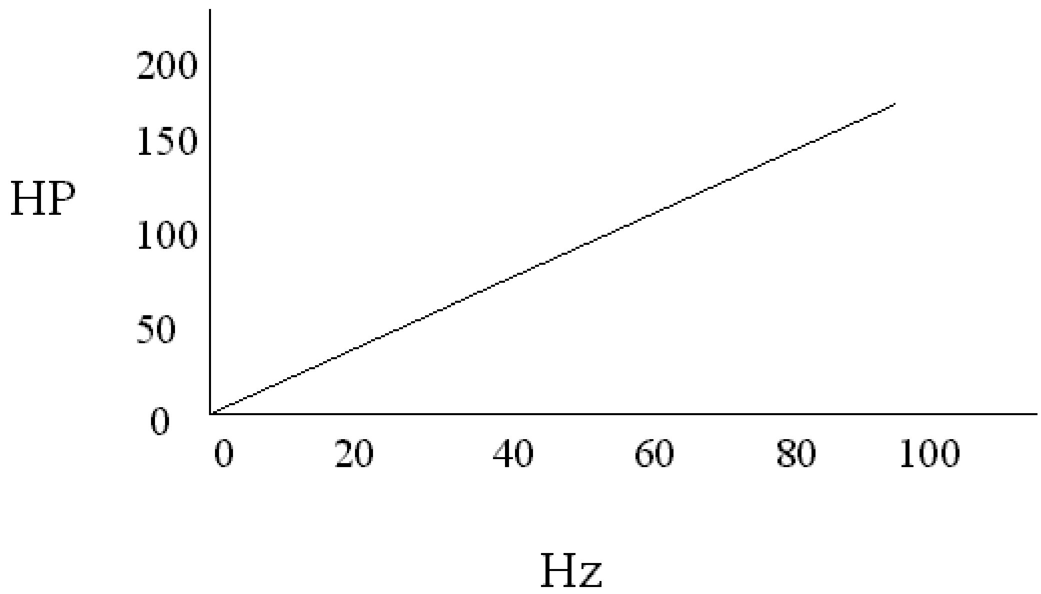
ESP – VSD

The VSD gives flexibility to the otherwise fairly inflexible ESP system -- at a price.

The frequencies possible with a VSD are from 20 to 100 Hz.

The motor horsepower output is a function of frequency. The higher the frequency, the more the horsepower.

$HP_2 = HP_1 * Hz_2/Hz_1$

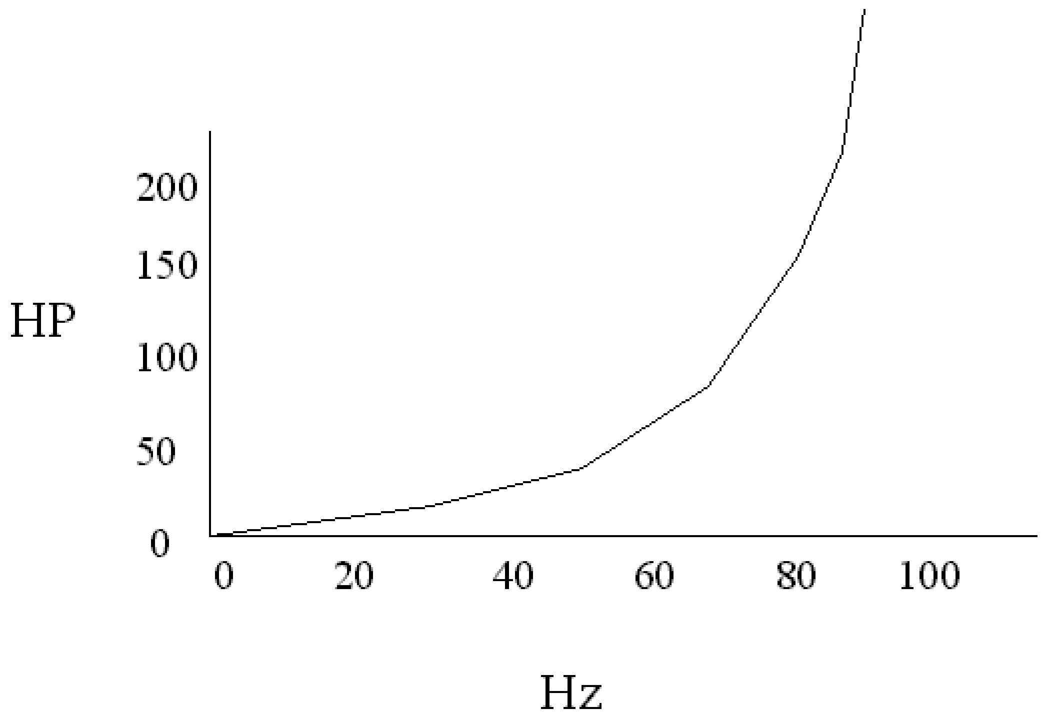


This is why smaller motors can be used if using a higher frequency.

ESP – VSD

The VSD gives flexibility to the otherwise fairly inflexible ESP system -- at a price.

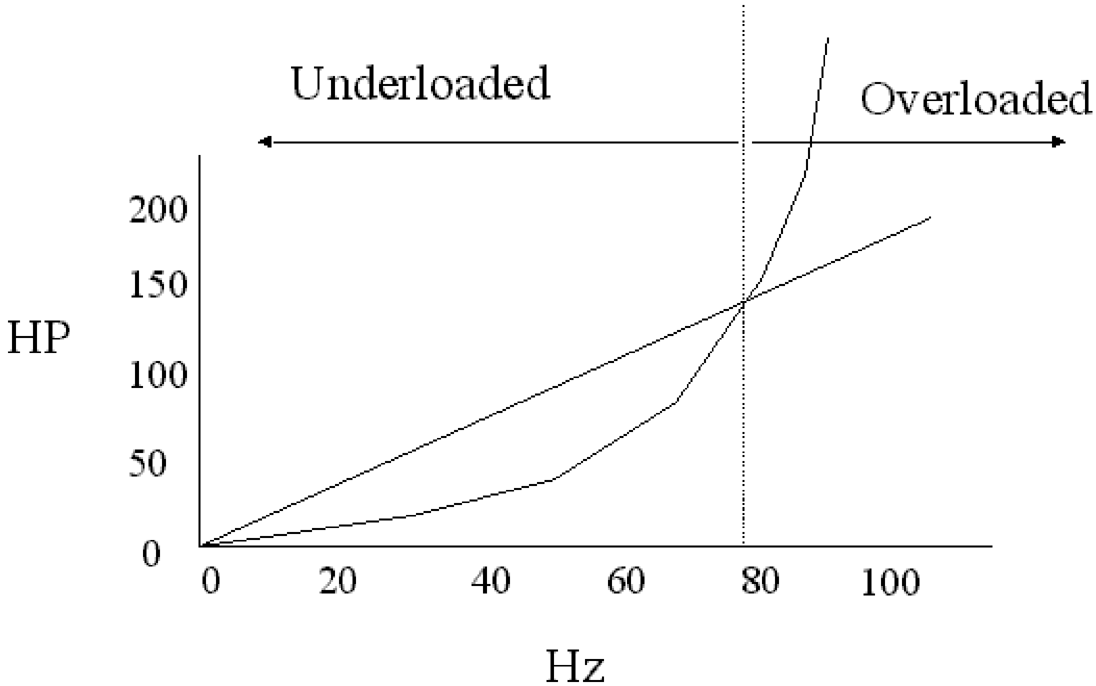
The pump horsepower required is a function of rotational speed (frequency) cubed. The higher the frequency, the more the horsepower required:
$HP_2 = HP_1 * (Hz_2/Hz_1)^3$



ESP – VSD

The VSD gives flexibility to the otherwise fairly inflexible ESP system -- at a price.

This means that up to a certain frequency, the motor is underloaded, and over that frequency the ESP cannot be operated because the motor is overloaded.

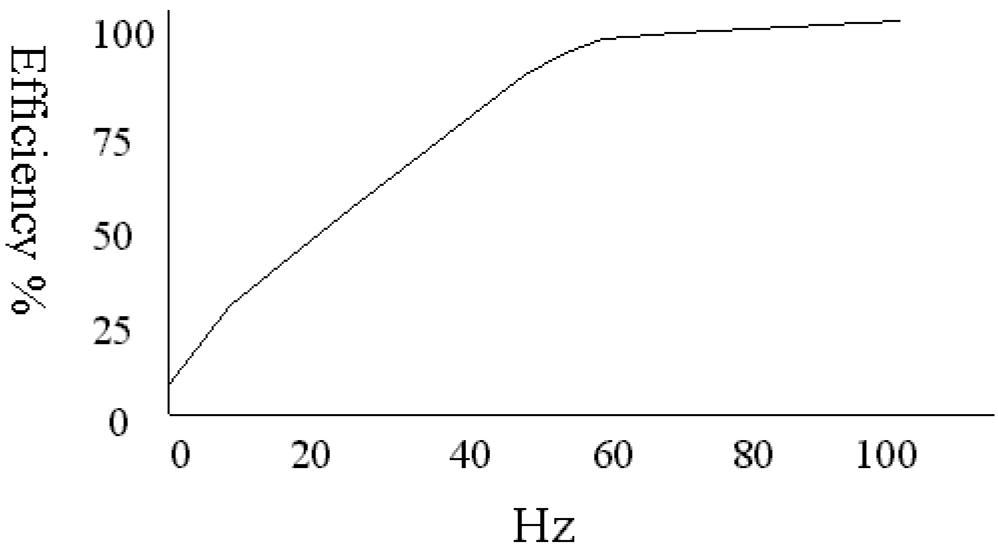


This gives an upper limit to the frequency possible for a given an ESP system.

ESP – VSD

The VSD gives flexibility to the otherwise fairly inflexible ESP system -- at a price.

At lower frequencies the electrical losses in the VSD can be severe. Here is a typical efficiency curve:



Also, at lower frequencies, harmonics in the system may create harmful voltage spikes. A typical operational range for an ESP system is 40 - 75 Hz.

9.1 ESP Cable and VSD Questions

How many power conductors does an ESP cable have?

Name the components of an ESP cable?

Near the pump a ____________ cable is typically used and this requires a field __________.

What can happen when the pressure is let off of an ESP cable hung inside a well?

A VSD is used to
a.Increase the reliability of the ESP system
b.Increase the range of operation of the ESP system

Name two drawbacks about VSDs:
____
____

ESP Cable and VSD Questions

A motor running on a VSD is
a. overloaded at high frequency
b. underloaded at high frequency

Horsepower supplied by the motor increases by:
a. $HP_2 = HP_1 * (Hz_2/Hz_1)$
b. $HP_2 = HP_1 * (Hz_2/Hz_1)^3$

The lower range of a VSD is limited by _____________

10 ESP – Operation

How do we monitor the operation?

The current draw by the motor is related to horsepower by
I = 746 * BHP / (PF 1.73 V)

where:

PF=power factor (.7 - .9)

V=voltage

I=current

We can monitor the current draw through the units ***recording ammeter***.

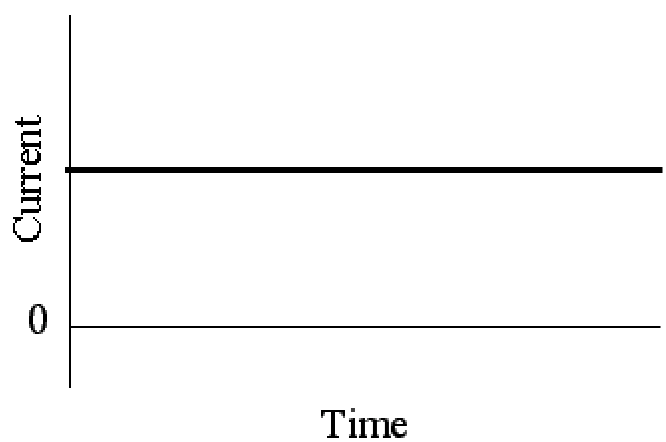
The normal configuration of the recorder is circular, but is shown linear in this presentation for clarity.

ESP – Operation

How do we monitor the operation?

The switchboard power cables are run through a current transformer. One leg of the switchboard power cable is monitored by the ammeter. The current transformer typically has two selectable tappings to get a ratio of 200:5 or 150:5. Also, the power cable can be looped through the current transformer a number of times, each time cutting the current in half.

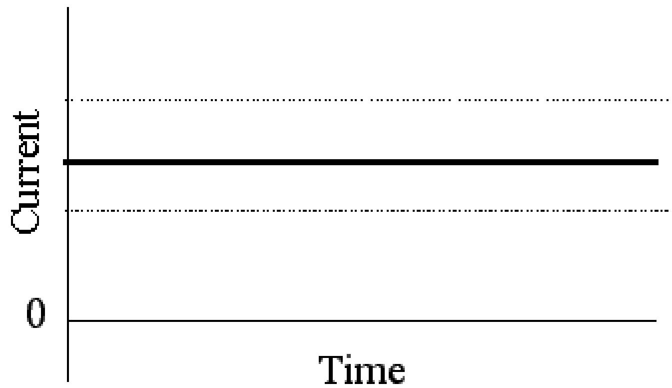
This allows the current to be monitored in the middle of the ammeter scale. The ammeter itself operates from 0 to 5 amps but will be set to represent normal operating current in the middle of the scale.



ESP – Operation

How do we monitor the operation?

The VSD or motor controller will have underload and overload shutdowns set to trip if the current is out its normal range.
The overload is typically set 20% over the normal operating current.



The underload is typically set 10% under the normal operating current.

ESP – Operation

How do we monitor the operation?

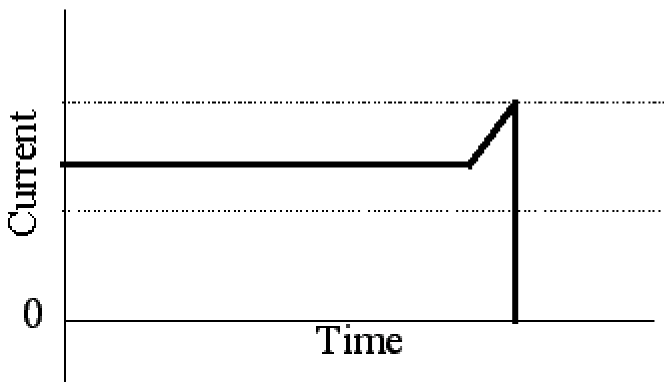
Overload may be caused by:

• Decreasing or increasing supply voltage

• Electrical failure

• Mechanical failure

• An increase in the density of the fluid pumped



Overload conditions may also be monitored by sensors on the current, voltage, and power factor in one or more phases. This allows the power supplied to the pump to be accurately measured and overload condition detected with greater precision.

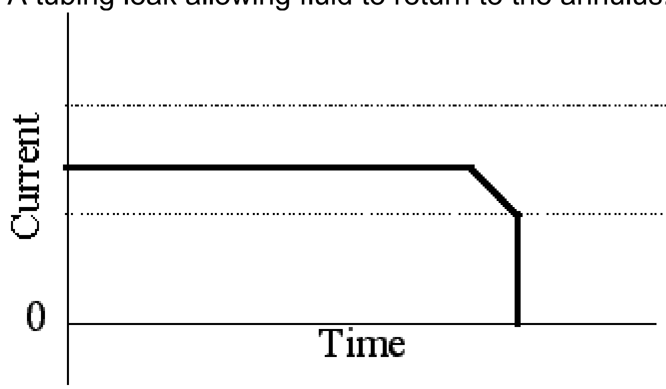
Because of the possible severity of the situation, restarting of the ESP on an overload condition should be done manually and after a complete diagnostic.

ESP – Operation

How do we monitor the operation?

Underload may be caused by:

- A ***pump-off*** condition where the fluid at the pump falls below the intake
- Cavitation in the pump
- Gas entering the pump
- Decrease in density of the produced fluid
- The closing of a valve, downhole or at the surface.
- A tubing leak allowing fluid to return to the annulus.

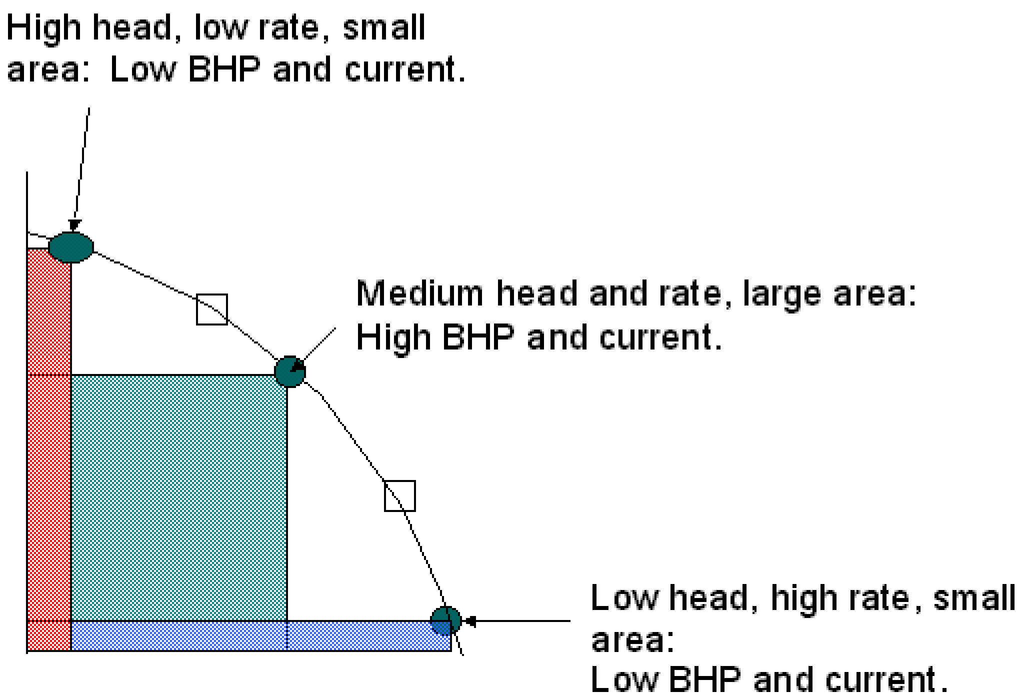


Underload conditions are sometimes set to allow automatic re-start after a time.

ESP – Operation

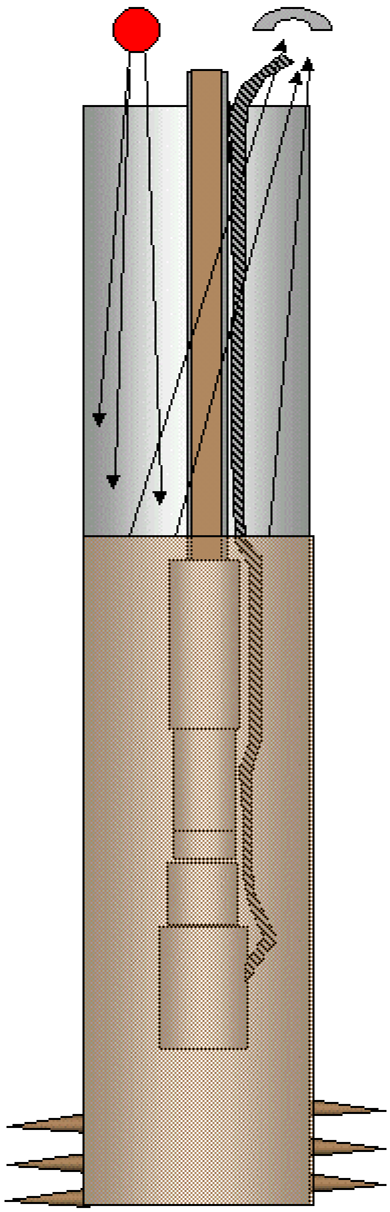
How do we monitor the operation?

One question that is often asked is:
Why is the current lower for things that cause more head (closing surface valve) and for less head (hole in the tubing)?
Remember that:
BHP = (rate) x (head) SG/(135771 Efficiency)
If you look at the head curve for the pump, BHP shows up related to ***area under the curve***: width x height = ***rate* x *head***.



ESP – Operation

How do we monitor the operation?



Another mechanism is the fluid-shot or acoustic level measurement. This device sends a pulse of sound down the annulus and listens for the echo.
The time delay determines the fluid level.
Since the well has no packer, the fluid level is in proportion to the FBHP.
If you know the rate, the FBHP and the SBHP, you know the inflow performance.
Be careful trusting these measurements as foam on top of the liquid level can give an artificially high FBHP indication.

ESP – Operation

How do we monitor the operation?

On a daily basis someone should record operating information on each ESP:

• current

• tubing pressure

• casing pressure

• hertz

• choke setting

• bottomhole pressure from downhole sensors.

• plot welltests on the pump curve.

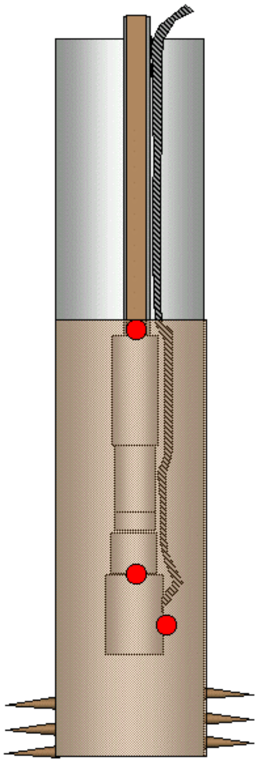
• note spikes and shutdowns on the ammeter chart

By doing this you will understand what is normal.

Troubleshoot any things that don't seem normal.

ESP – Operation

How do we monitor the operation?



We may also install special monitoring equipment that can send signals either up the power cable or up an extra cable.

Possible measurements are:

• intake pressure

• discharge pressure

• discharge temperature

• downhole flowrate

or, less commonly:

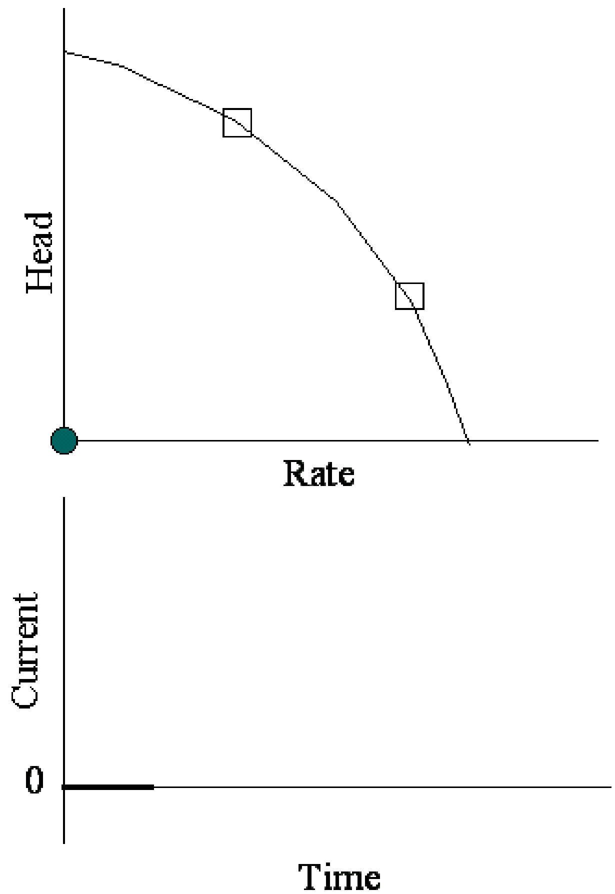
• vibration

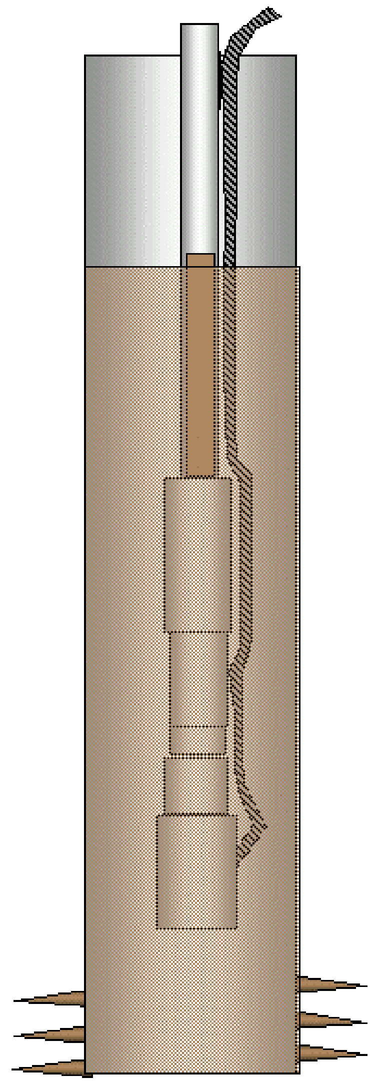
• motor temperature

ESP – Operation

What does normal ESP operation look like?

Before starting the pump, the fluids in the well start out equalized (assuming there is no packer installed).

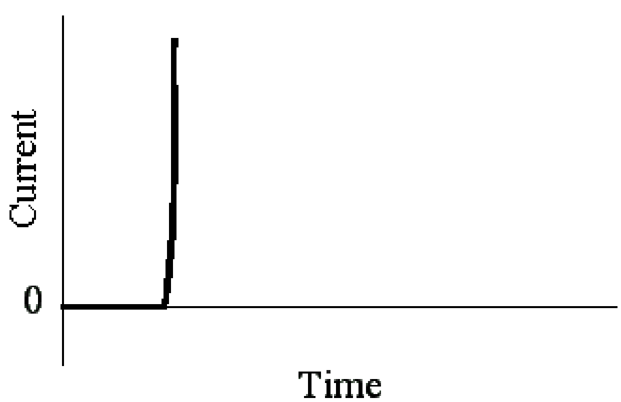


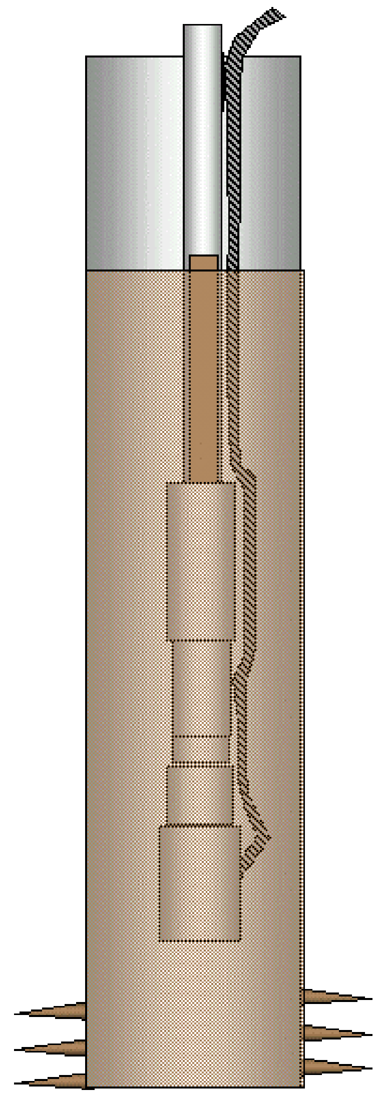


ESP – Operation

What does normal ESP operation look like?

When the pump is started, the whole assembly -- the motor rotor, the shaft, the impellers -- must go from zero up to the design speed, about 3000 rpm. Accelerating all of this metal and the liquid inside the pump requires 2-5 times the operating current.





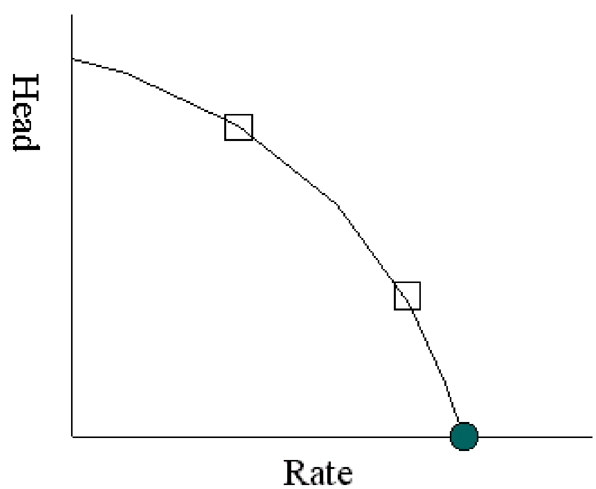
The overload and (usually) the underload shutdowns are over-ridden during start up.

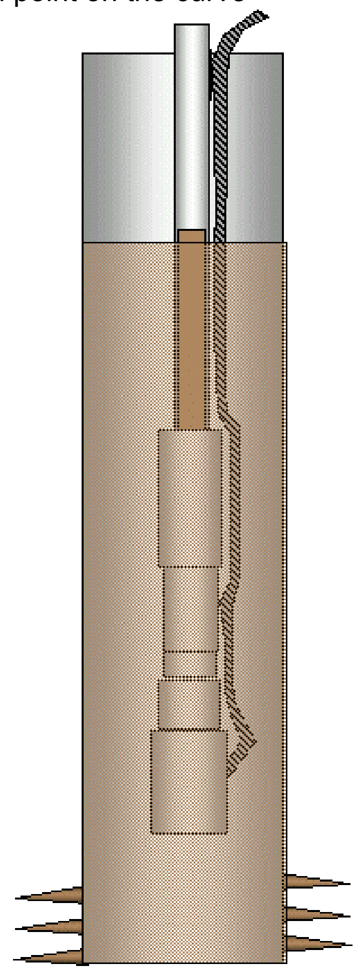
[VSDs include a feature called soft-start that extends the time required to reach full speed and thus limits the current draw and stress.]

ESP – Operation

What does normal ESP operation look like?

Since the fluids in the well are equalized, there is no head for the pump to have to overcome. The operating point is temporarily at the maximum point on the curve

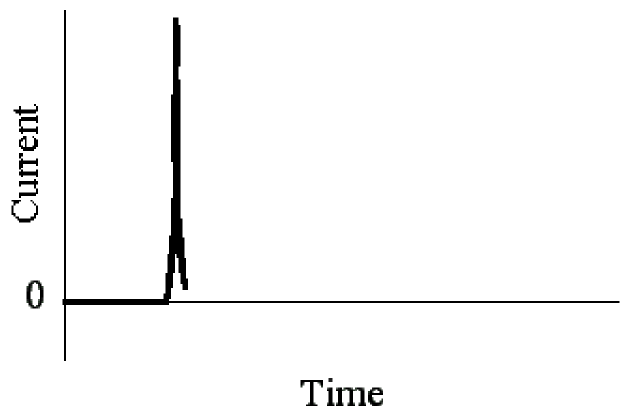


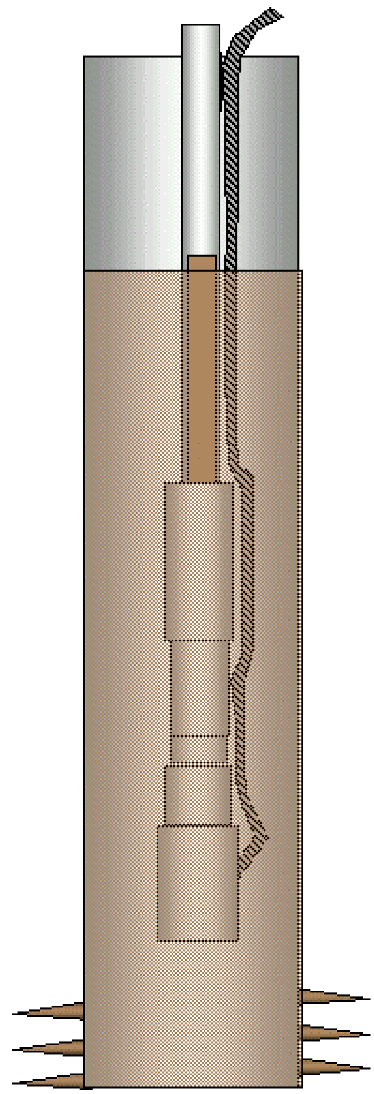


ESP – Operation

What does normal ESP operation look like?

The current will fall after the rotors are up to full speed. Actually at this point the current is at a low level because the head is low.

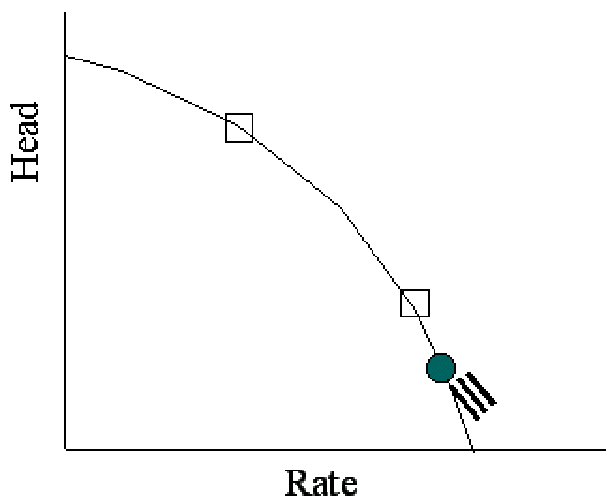


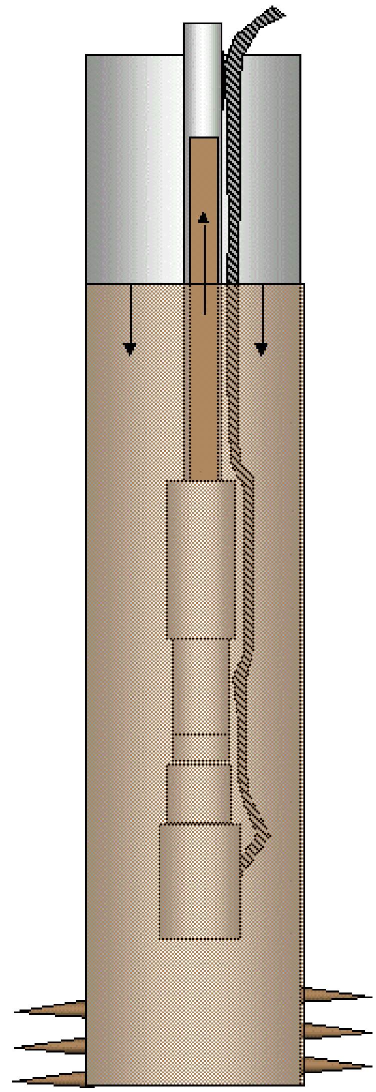


ESP – Operation

What does normal ESP operation look like?

As the fluid in the tubing rises the head will increase. Also the fluid in the casing will fall as the FBHP falls and the rate from the formation increases.

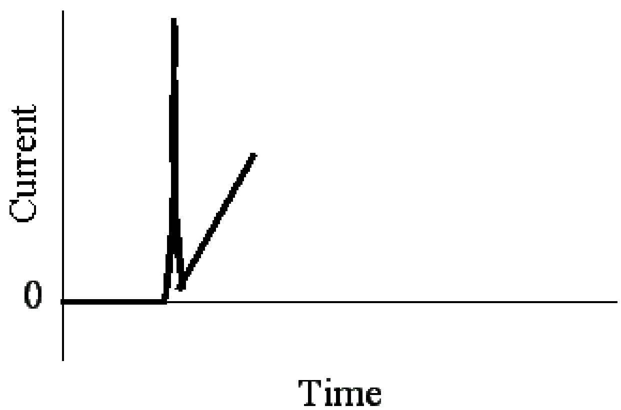


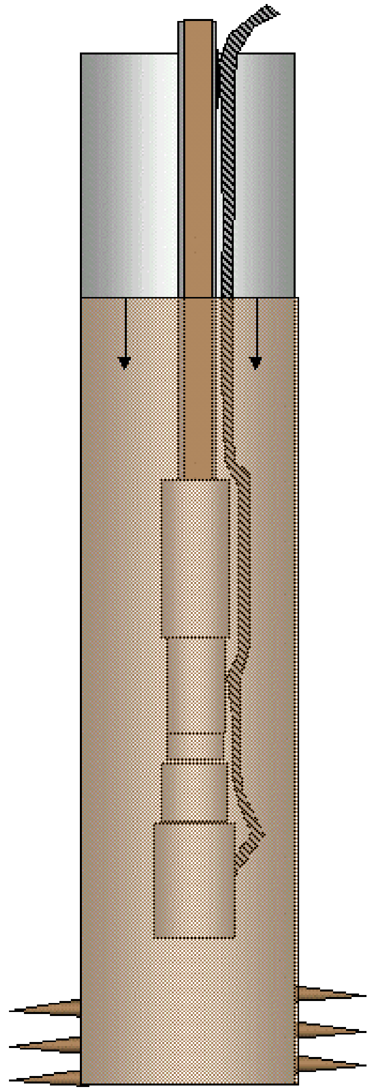


ESP – Operation

What does normal ESP operation look like?

The current will increase as the head increases and fluid is pushed to the surface, and as the fluid creates friction in the tubing and the flowline.

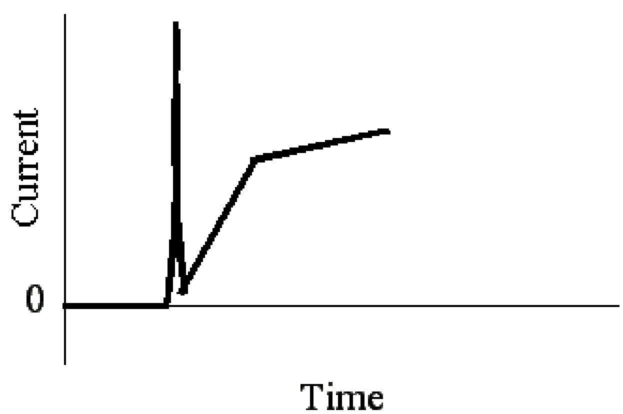


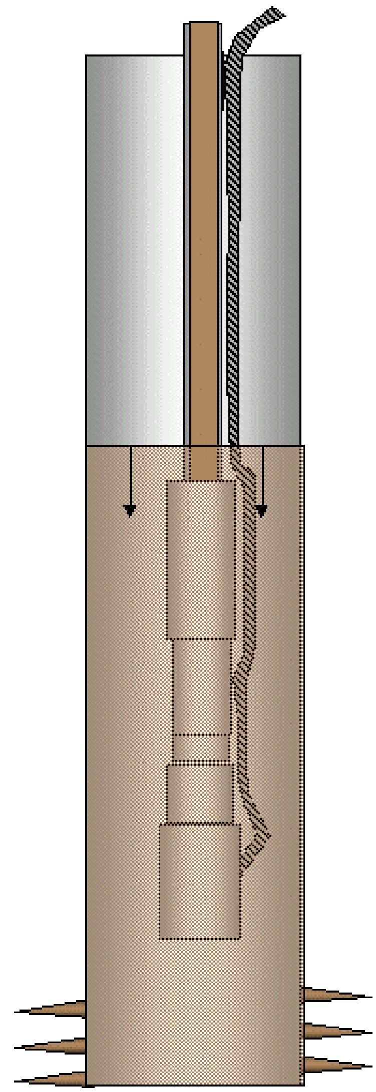


ESP – Operation

What does normal ESP operation look like?

Depending on the drawdown, there may be some additional head as the level in the casing is pulled down to the operating level.

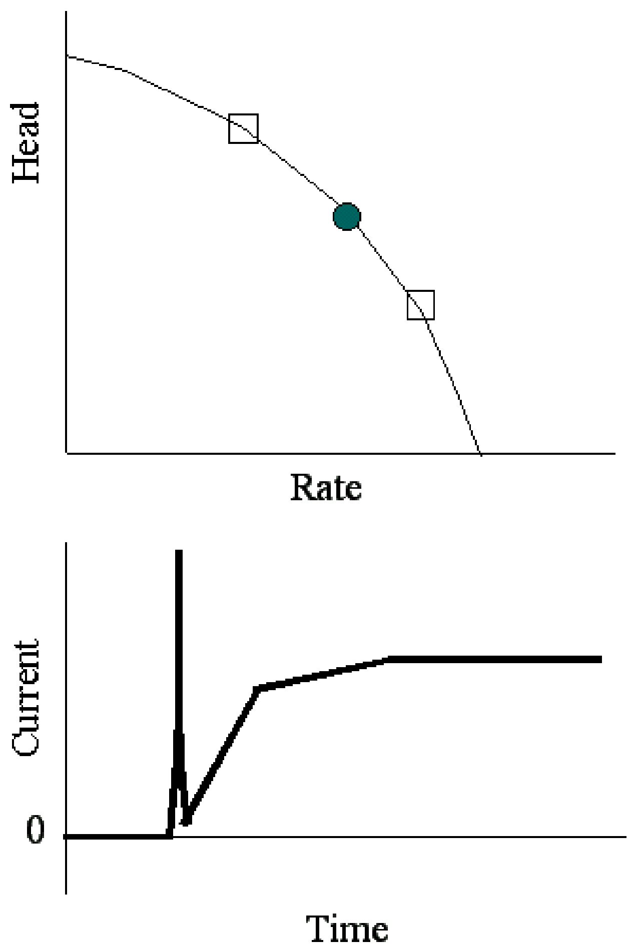


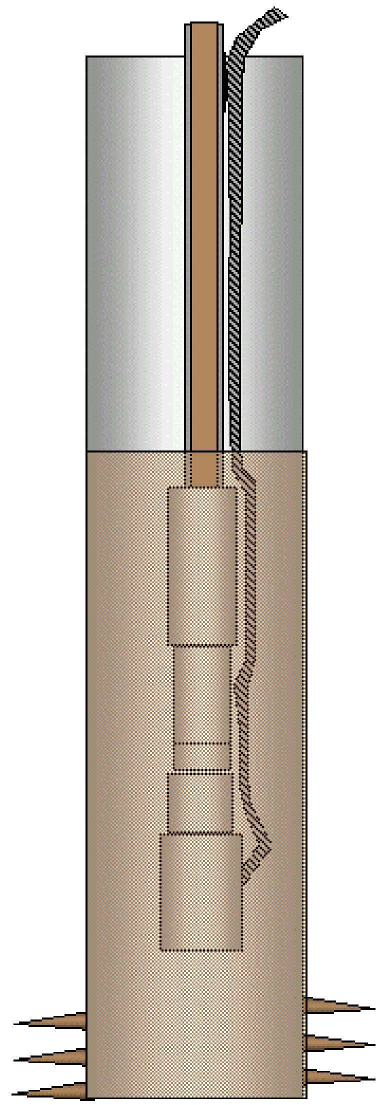


ESP – Operation

What does normal ESP operation look like?

Once the fluid levels have reach the operating points, the head will be constant and so will the current draw.

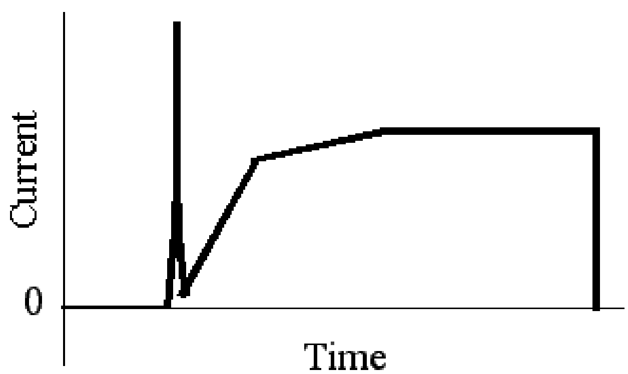


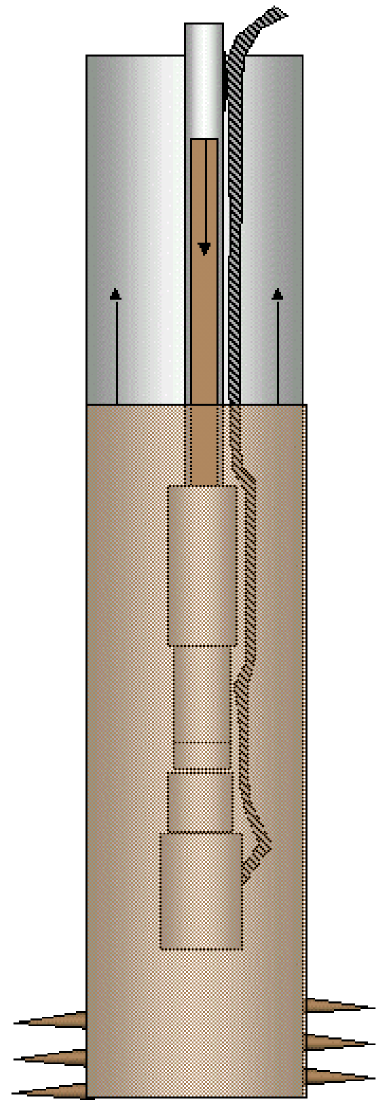


ESP – Operation

What happens when the pump is shut-down.

As soon as the current is switched off, the motor quits providing thrust.



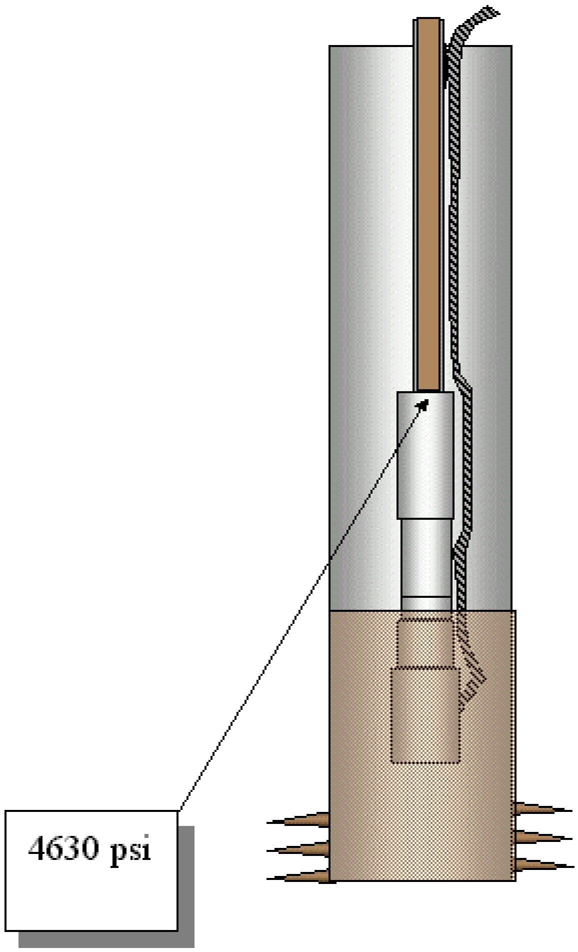


The fluid level in the tubing must equalize with the casing. Pumped fluid falls back through the pump. This backspins the impellers which does not harm the pump or motor.

However, if the ESP is switched on while backspinning the load on the shaft will be tremendous and will break For this reason the controller has a delay and/or a backspin detector to prevent this.

ESP – Operation

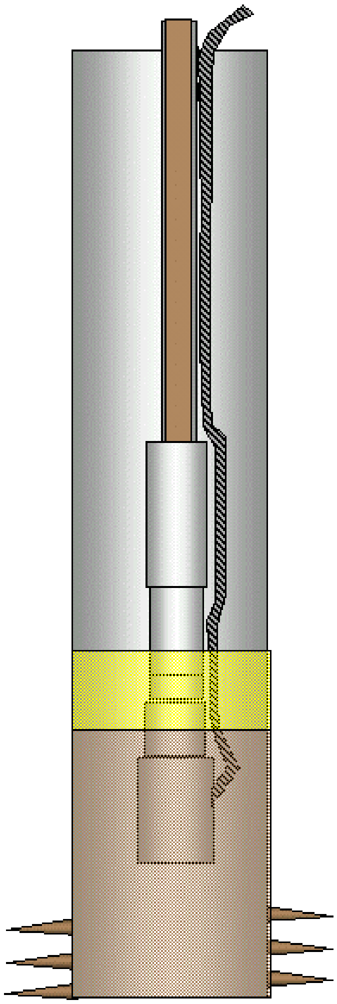
Lets see what happens in our well if we get some gas into the pump.



Remember that the pump is a constant head device. The head generated by the pump is the same for a given rotational speed.
Lets say that the fluid level is near the pump, at about 9800' and if we again assume the same friction and ftp head, the TDH=9800+245+444= 10289'. The pump is generating this much head.If the fluid through the pump were 0.45 psi/ft, the pressure at the pump would be 10289 * 0.45 = 4630 psi.

ESP – Operation

Lets see what happens in our well if we get some gas into the pump.



If gas enters the pump, the fluid in the pump will have a lower density, perhaps .25 psi/ft. The pressure at the outlet of the pump would be 0.25 * 10289 = 2572 psi.

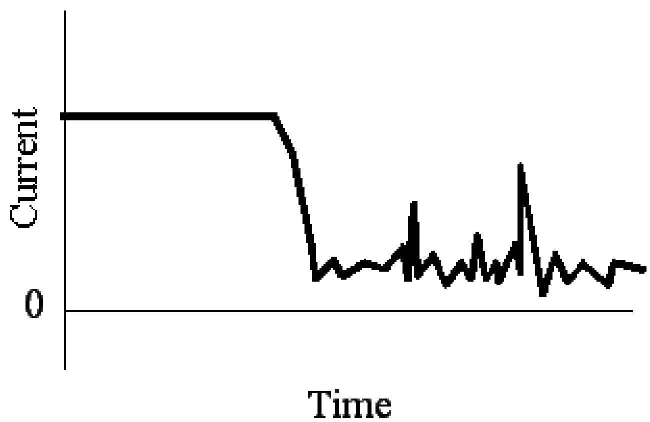
This is not good because there is still 4630 psi above the pump.
[Actually, since the rate is much less, we have only the weight of the liquid plus the ftp, about 4430 psi above the pump.]

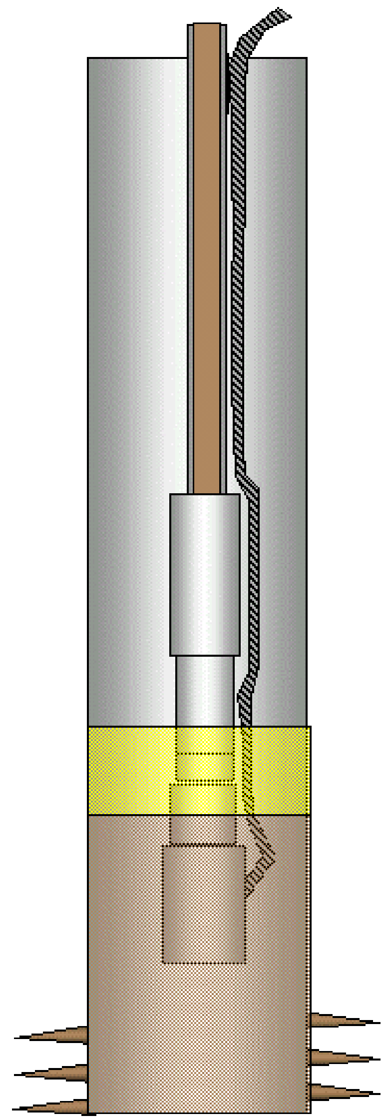
At this point either the fluid above the pump would try to fall back through the pump, or if a check valve were installed above the pump, the pump would spin with gas inside. Either way, the rate through the pump falls to near zero and the pump is ***gas locked***.

ESP – Operation

How do we know if we have gas in the pump?

Since the rate is near zero, the BHP would fall.

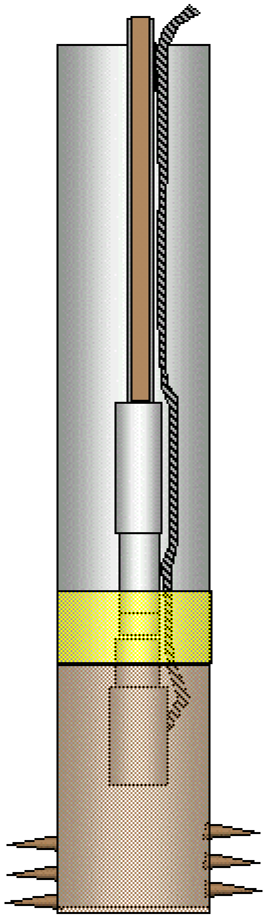




The pump creates flow when enough liquid is in the pump, then fails to create flow once gas is drawn in.
This causes a low and erratic current load on the pump.

ESP – Operation

Why shut-down the pump automatically if gas locked?



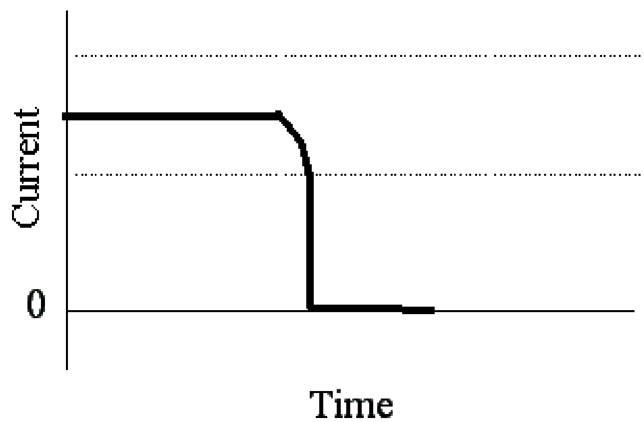
The only thing cooling the motor is the liquid flow past the motor.

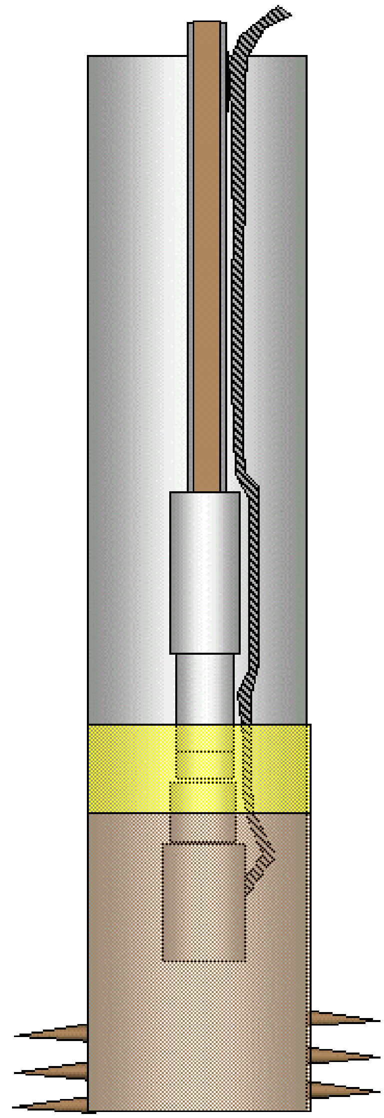
With the rate approaching zero the motor temperature will rise.
Also, gassy fluid cannot carry as much heat away from the pump so this too will increase the motor temperature.
The lubricity of the fluid inside the pump with gas is very poor, possibly leading to pump seizing.
If the motor temperature rises too high the motor will seize.
This is why we must be so careful not to let too much gas enter the pump.
Don't let the liquid level get below ~200' above the pump intake.

ESP – Operation

Why shut-down the pump automatically if gas locked?

If the underload is set properly, it will trip and the ESP will be shutdown.



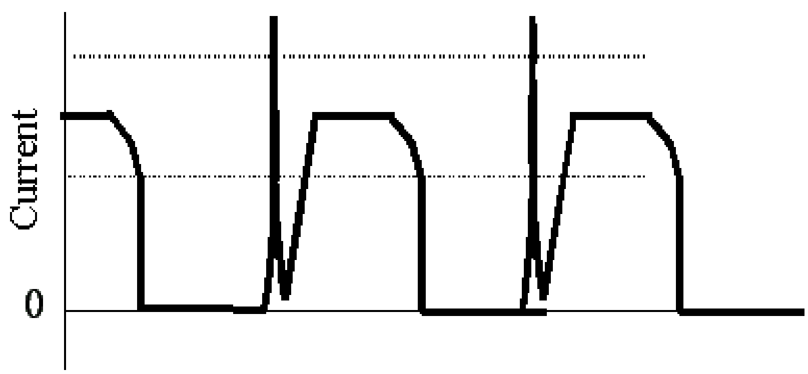


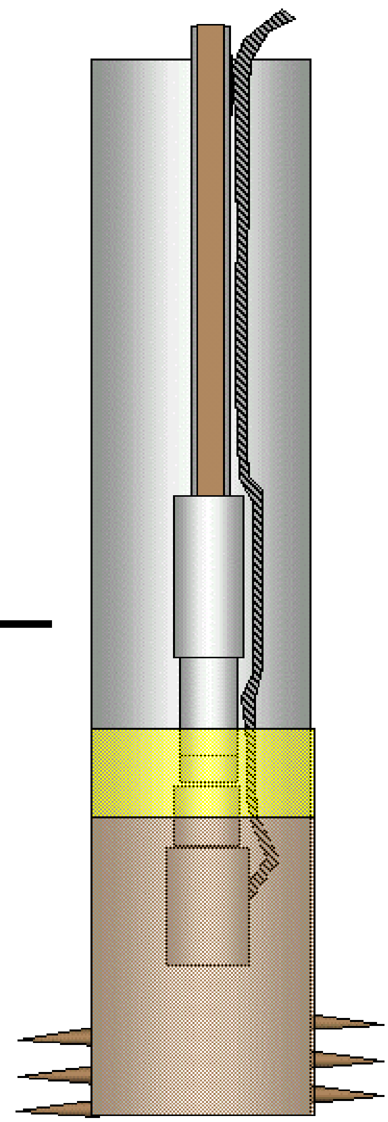
ESP – Operation

How do we know if we have gas in the pump?

Some systems may allow automatic re-start on underload.

However, re-occurring starts are not desirable.



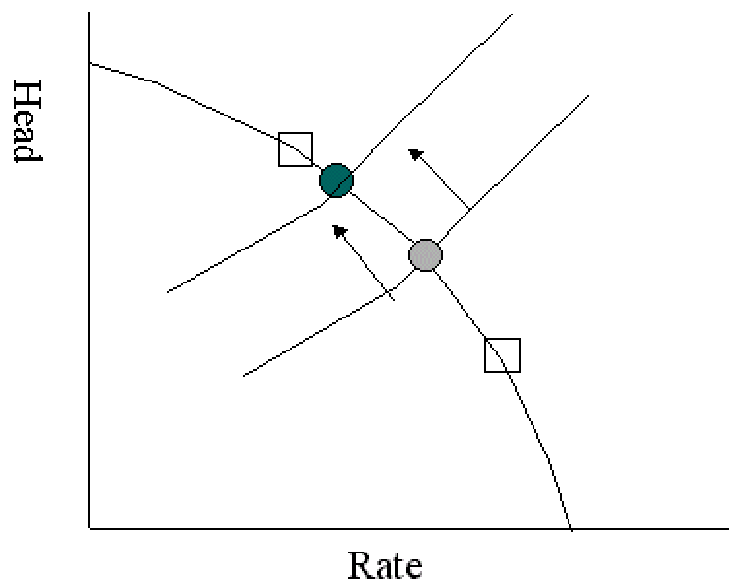


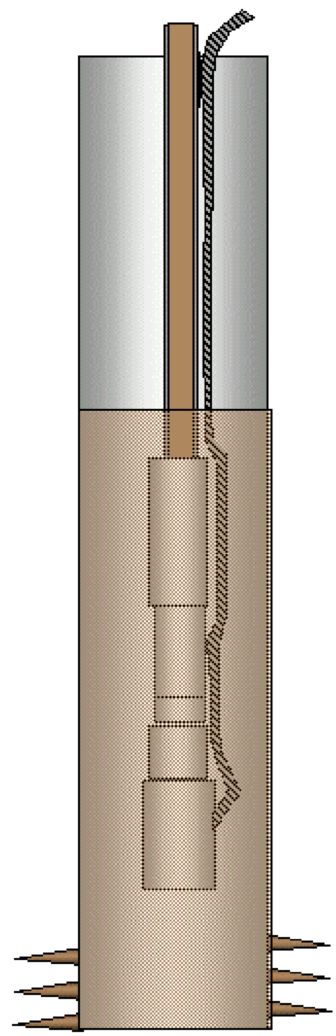
Because of the heavy mechanical and electrical loads during start-up, this on/off operation will greatly shorten the life of the ESP.

ESP – Operation

What can we do if the pump is taking in gas?

The gas is probably either coming from the annulus due to a low fluid level, or is being coned into the well in the reservoir. Either way, raising the FBHP will help
Because of the inflow performance behavior, the production rate must fall.
The well can be choked back at the surface to raise the FBHP.

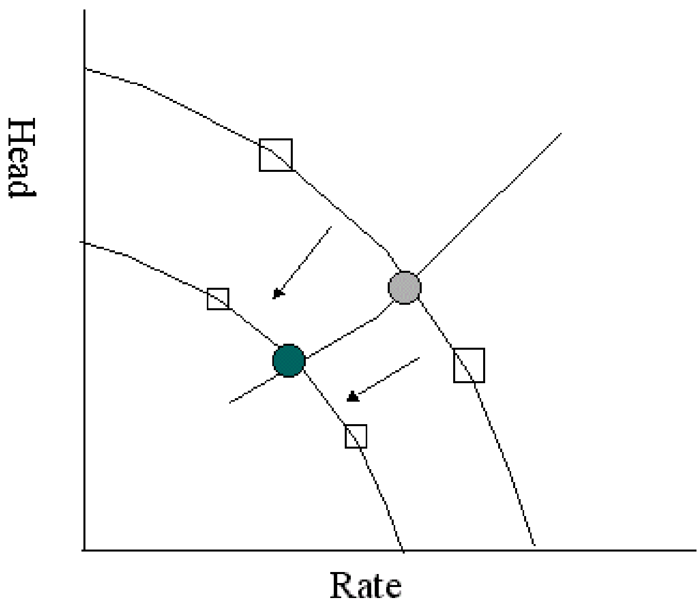


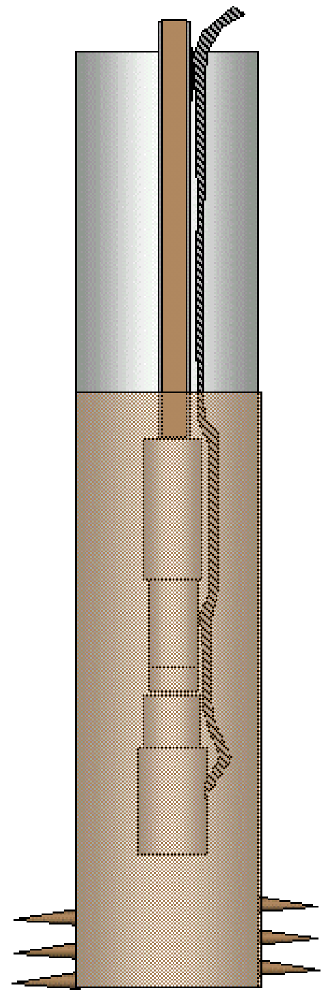


ESP – Operation

What can we do if the pump is taking in gas?

Or, if we have a VSD, the speed can be lowered.

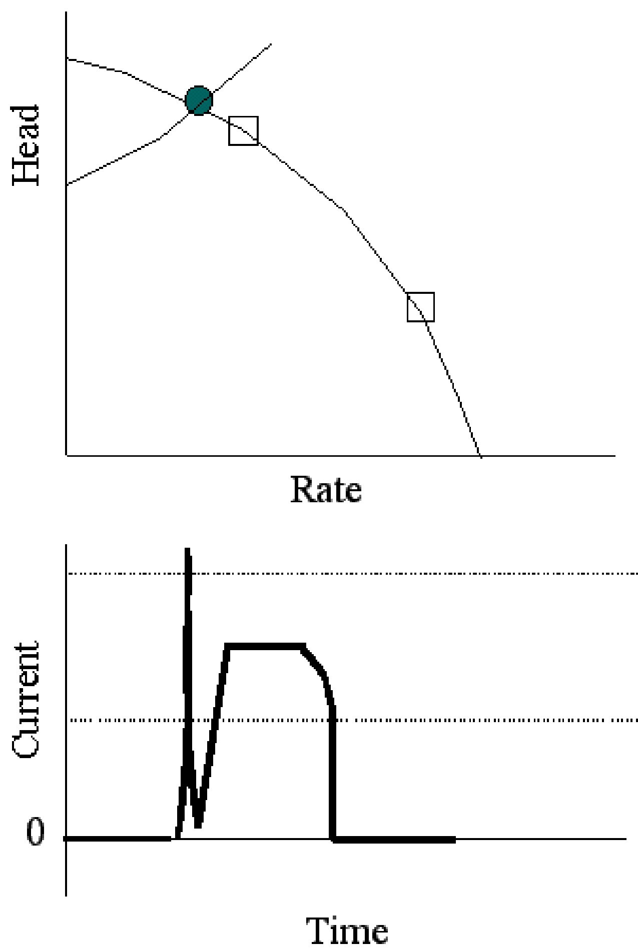


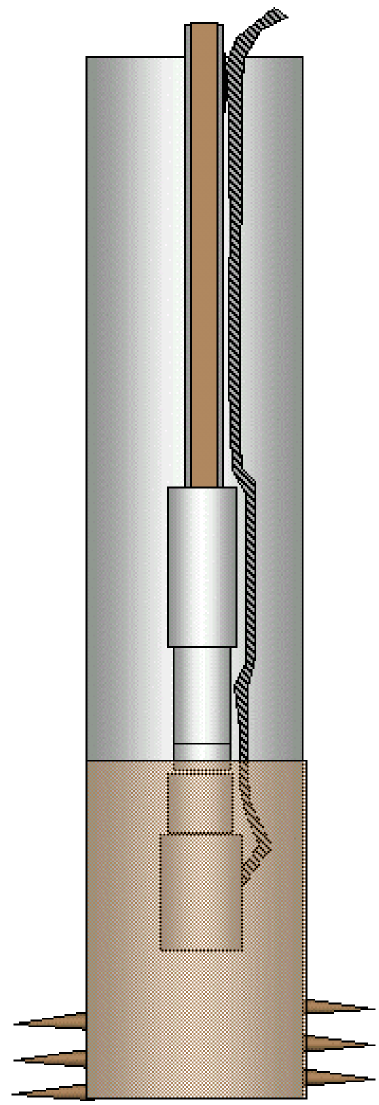


ESP – Operation

What if the inflow is too poor?

This can happen with natural depletion, plugging, or scaling.
The pump may go into downthrust.



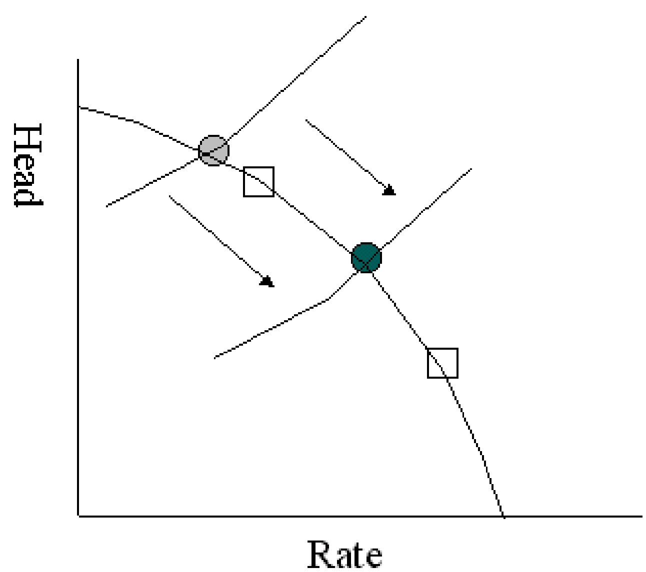


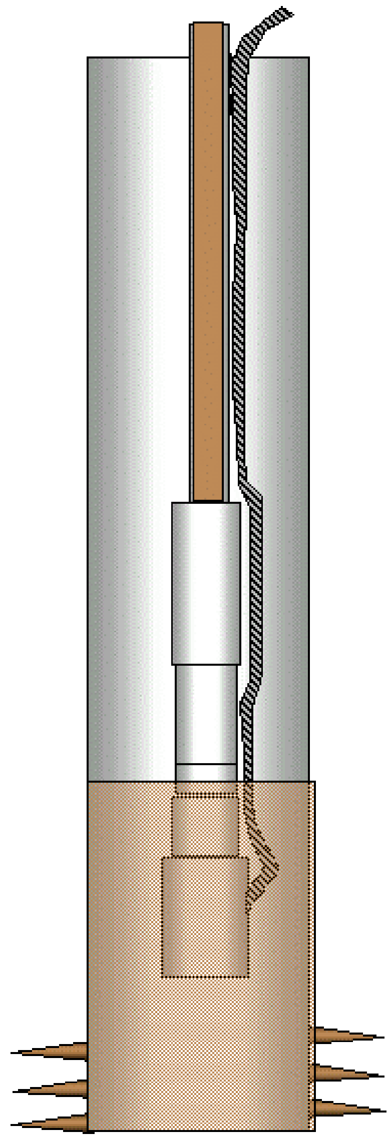
The fluid level will fall, pulling in gas and shutting down on underload

ESP – Operation

What if the inflow is too poor?

This problem is not easily corrected. Some engineers have routed fluid from the flowline back into the annulus to mimic an increase the well performance while waiting to replace the pump with a smaller unit.

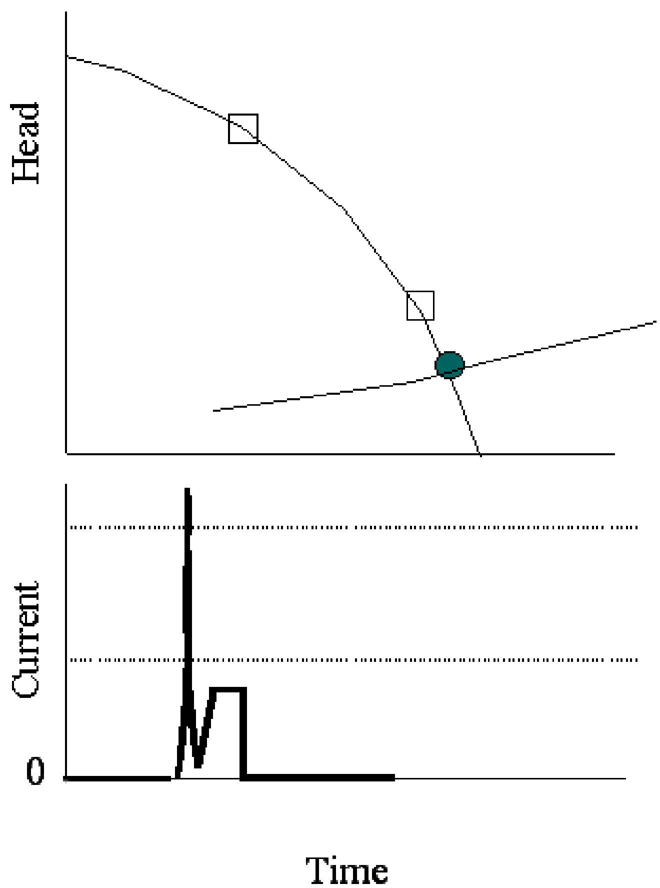


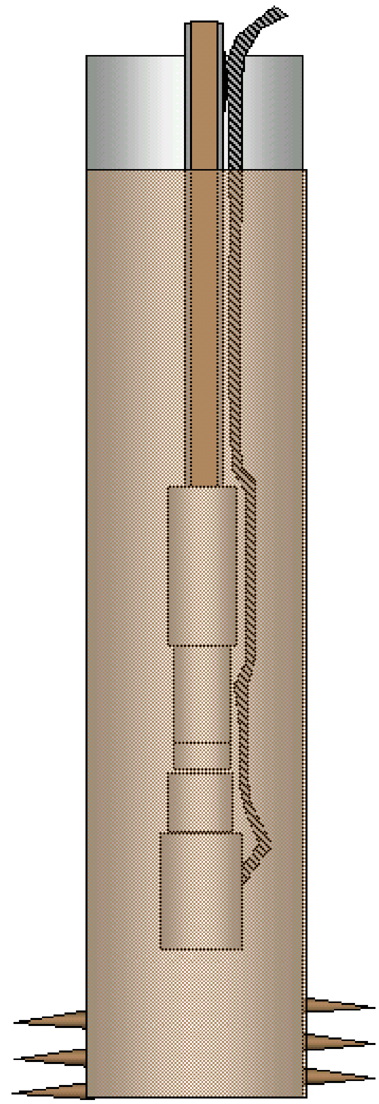


ESP – Operation

What if the inflow is too great?

This could happen after a stimulation in a well that no longer has high drawdown. The pump may go into upthrust.



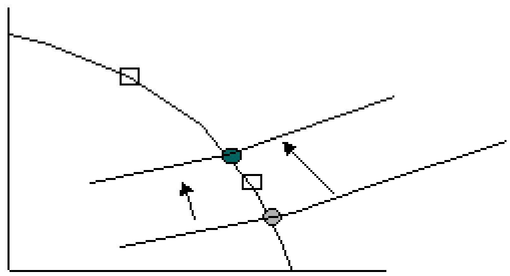


The horsepower required is much less since the head is lower. Thus, the current level may never reach the underload limit and may shutdown quickly.

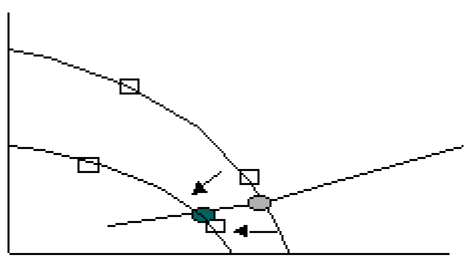
ESP – Operation

What if the inflow is too great?

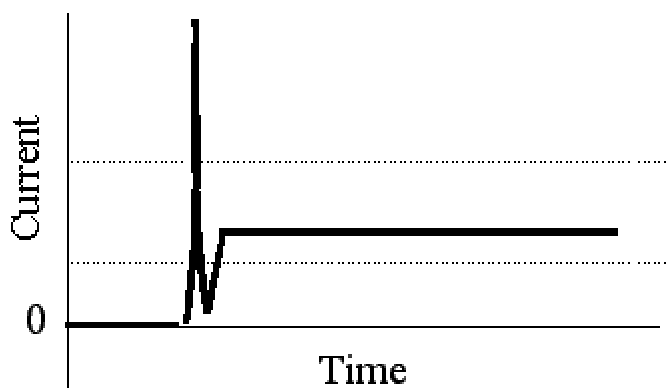
This situation can be fixed by choking the well back,

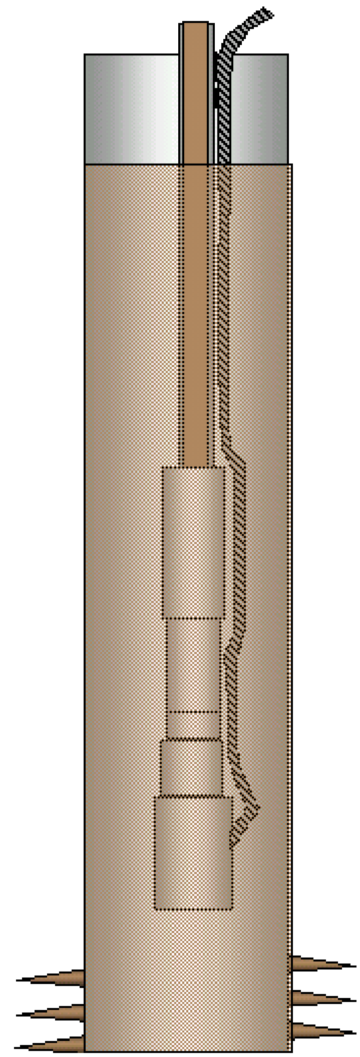


By lowering the speed,



Or if the upthrust is not severe, lowering the underload limit.

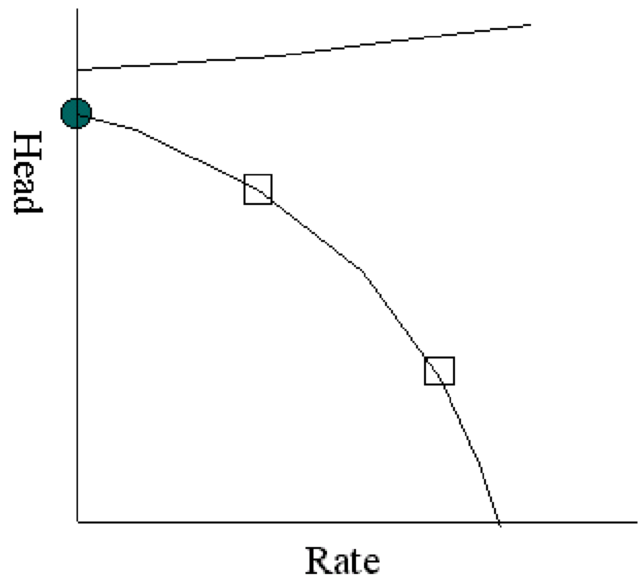


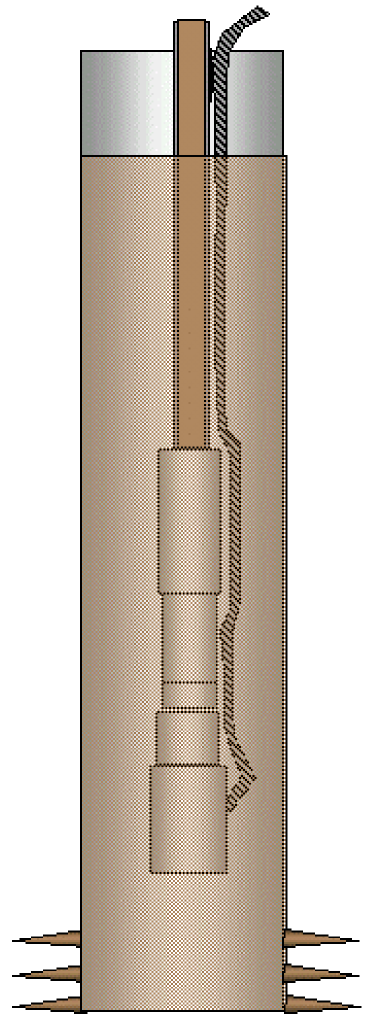


ESP – Operation

What happens if the well is shut-in at the surface?

When a valve is closed at the surface, the rate goes to zero and the head goes to the maximum.



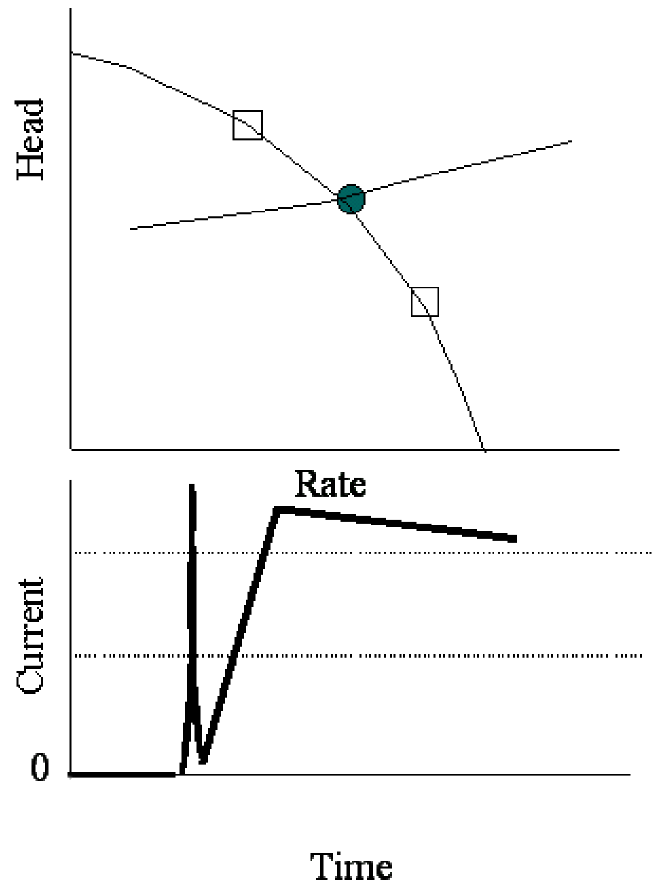


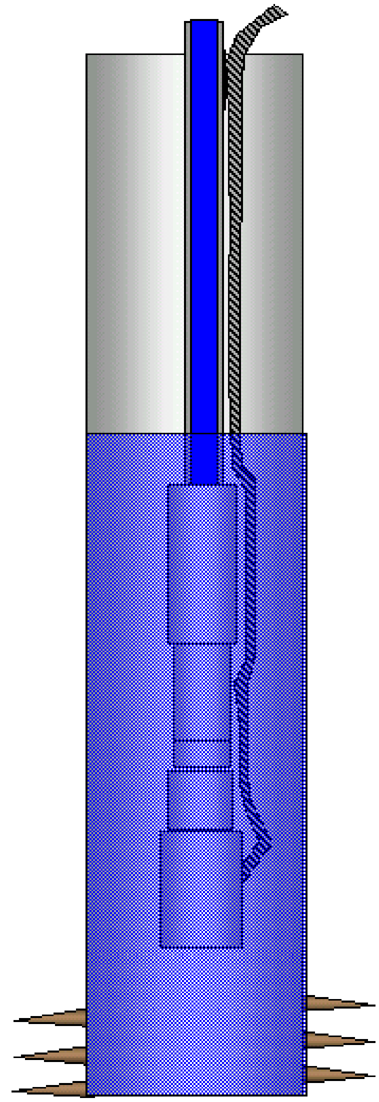
This can create very high pressures in the tubing. The tubing, flowline and pump housing must be designed not to burst under these conditions.
The horsepower required will fall as the rate through the pump falls and the pump will shut down on underload.
If not shut down the motor will overheat since there is no liquid flow for cooling.

ESP – Operation

What happens when heavy fluids are in the well?

This could happen after a stimulation or after installation when the completion fluid must be produced from the well.



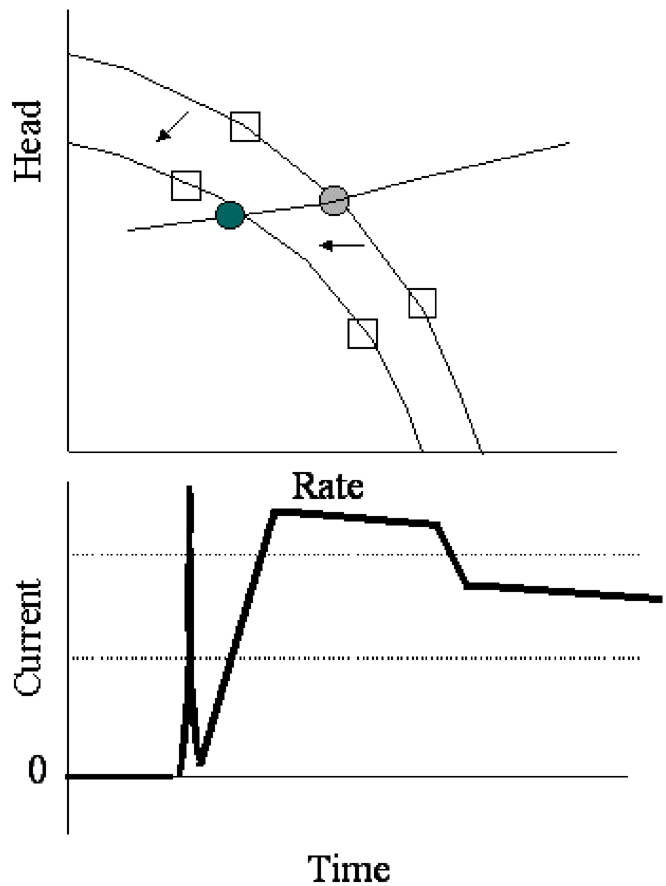


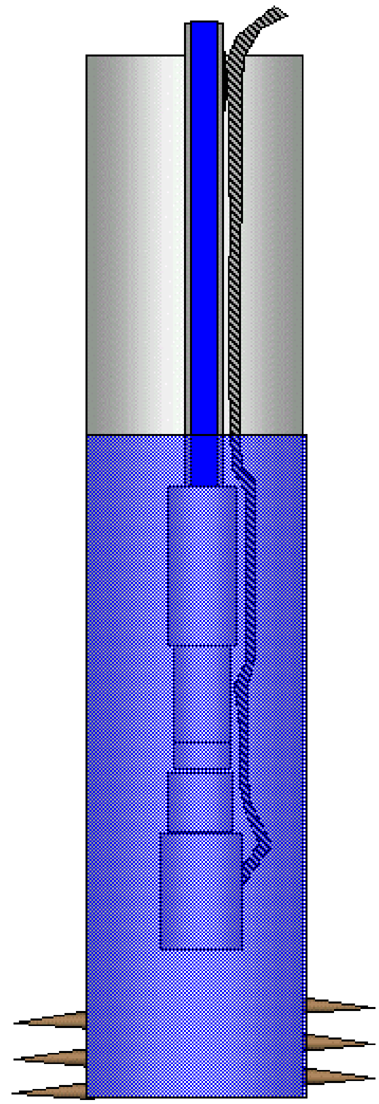
This may cause the overload limit to be exceeded. Eventually the heavy fluid will be replaced with the normal well fluids and the load will fall.

ESP – Operation

What happens after the well is killed?

Rather than raising the overload limit, if a VSD is installed, reducing the speed will reduce the current.

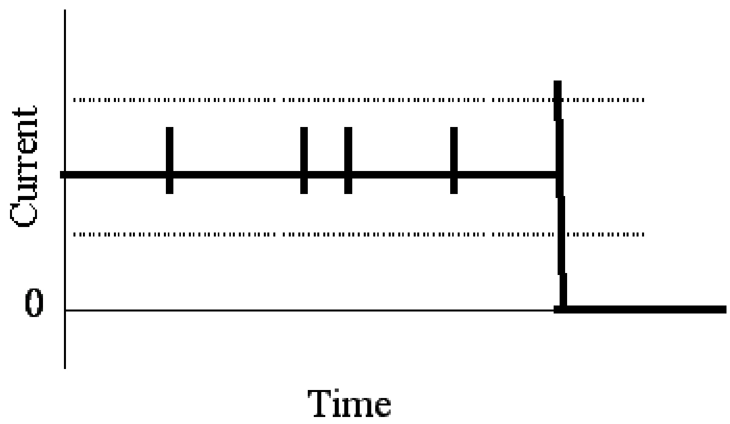


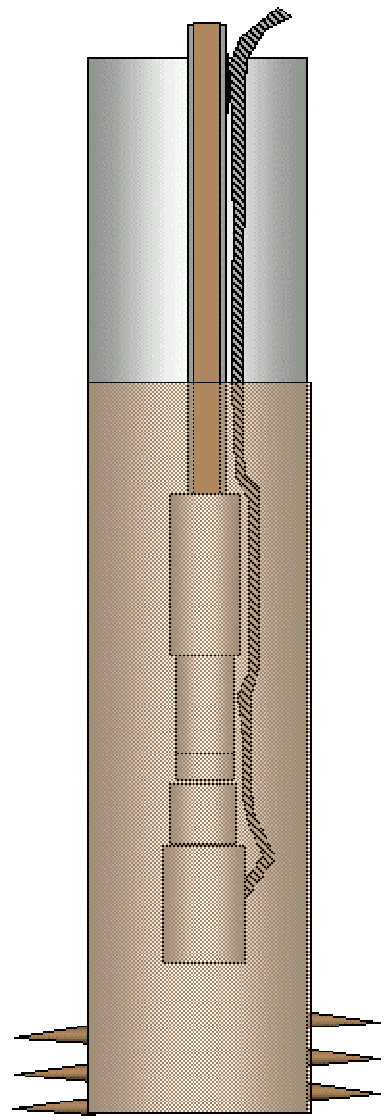


If the ESP was not designed for significant water production, and the current load is too high, obviously the speed can be reduced with a VSD to solve the problem long term.

What are those random spikes on the chart?

The current on the system varies inversely to the voltage supplied. If the voltage drops the current will increase to compensate.

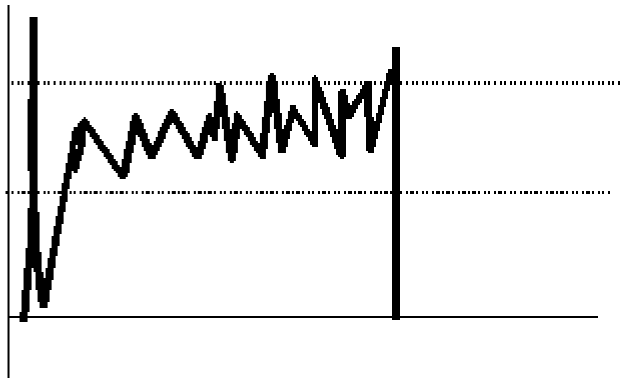


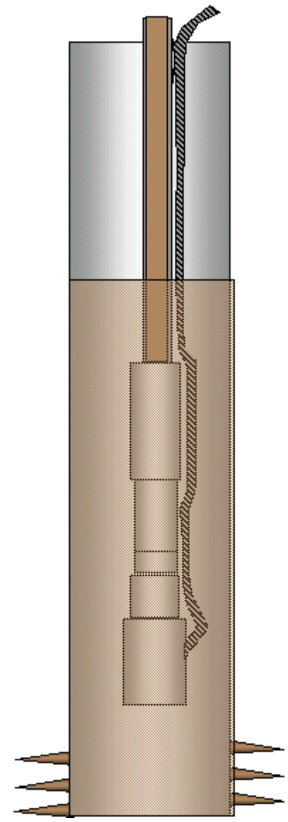


Voltage decreases are usually related to heavy loading of the power supply system, such as export pumps turning on. Lightning strikes can also cause these spikes. These spikes may cause equipment damage and may also cause spurious shutdowns.

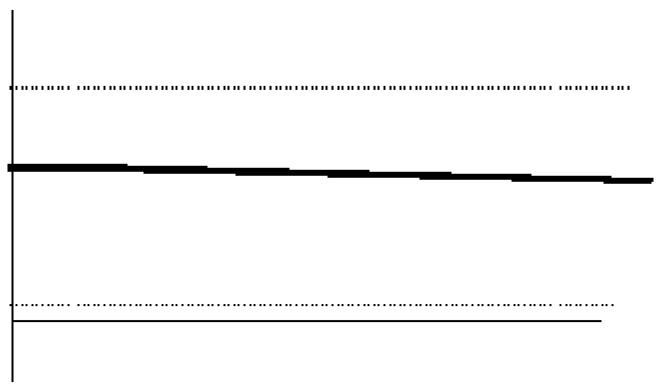
ESP – Operation

What are some other things to watch out for?





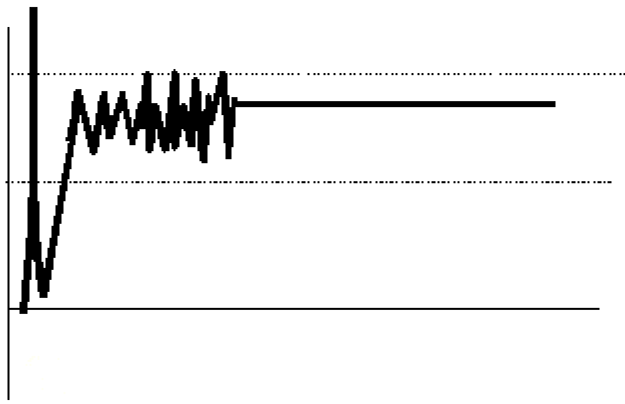
This chart could be caused by debris, increasing viscosity, damaged pump, etc. No restart should be made until the problem is investigated.



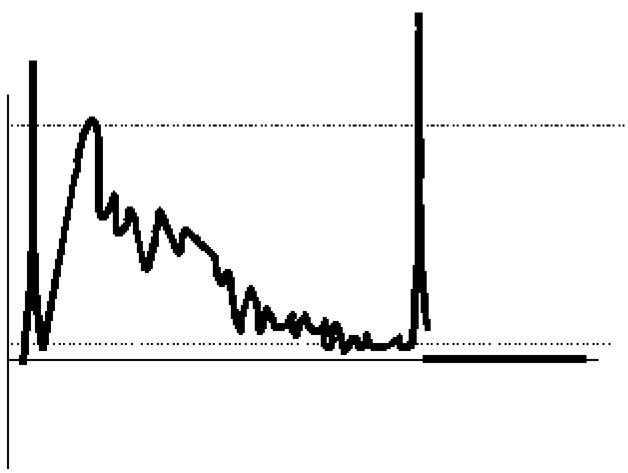
A very gradual drop in current could be caused by pump wearing or declining productivity.
Before replacing the pump, you must determine which is the case.

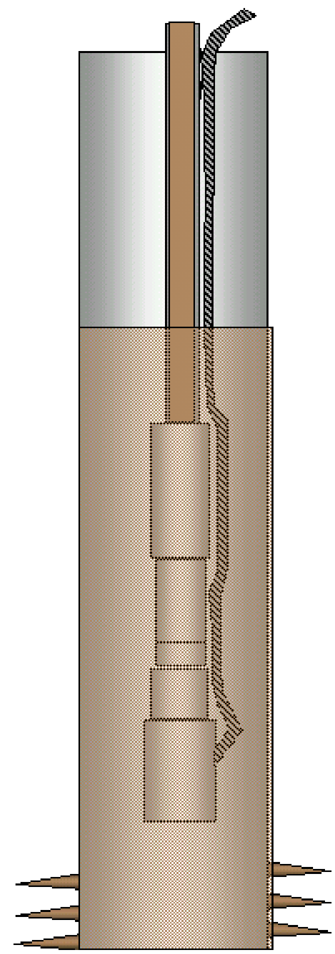
ESP – Operation

What are some other things to watch out for?



This chart could be caused by debris sucked into pump on startup which then clears.

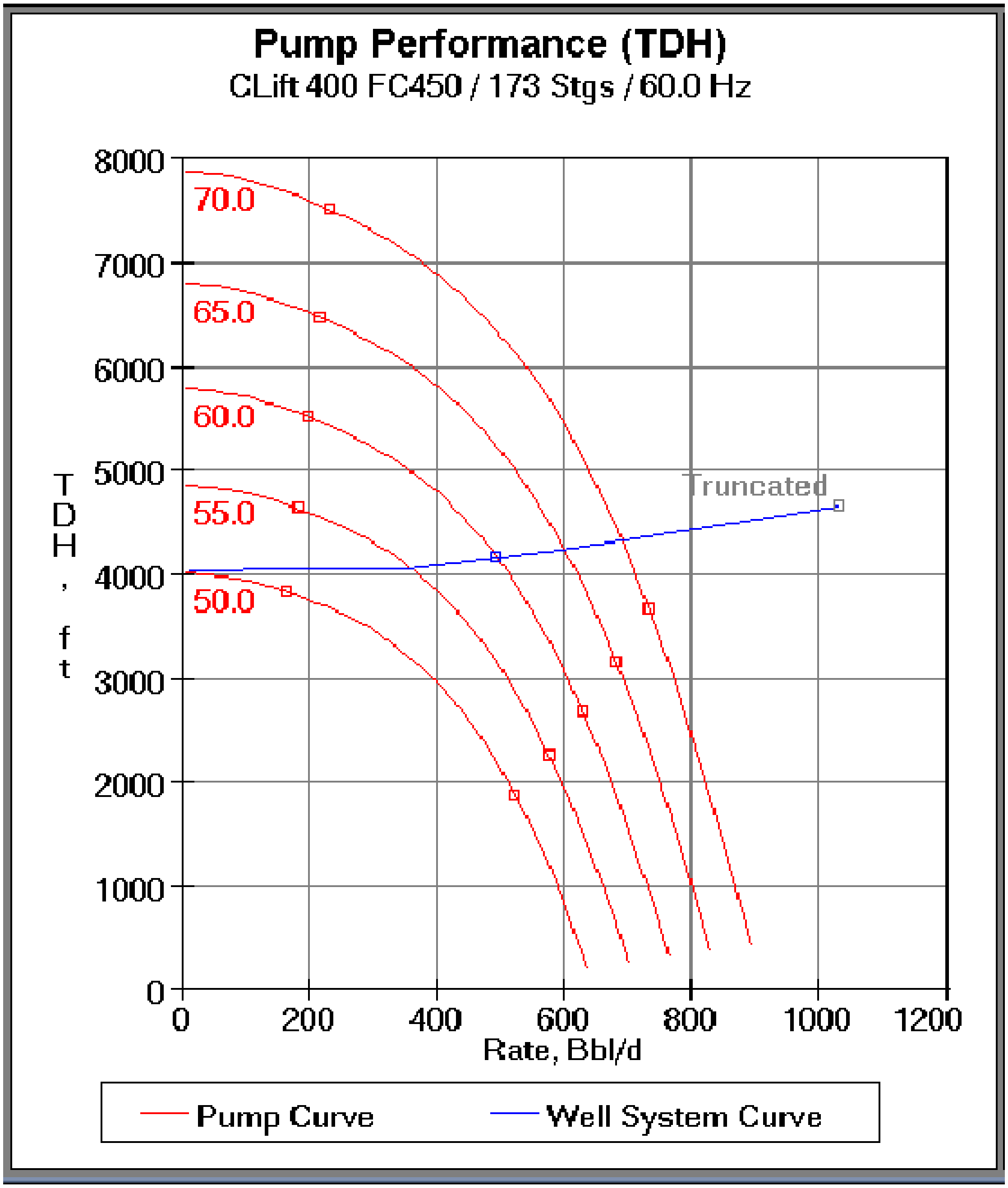




Here underload circuit failed to detect gas lock.
The motor burned and tripped the overload circuit.

Examples of ammeter charts can be found in API 11VS and vendor manuals.

ESP – Operation



Performance of the SMI-130 A7 system using SubPump
It looks like this well has an expected rate of about 460 bbl/d at the surface and a downhole volume of about 500 bbl/d. This falls in the middle of the 60 Hz curve.

ESP – Operation

Performance of the SMI-130 A7 system using SubPump

SubPump can calculate the rates at the intake, discharge and surface.

	Intake	Discharge	Surface
Oil Rate,	348.0	342.5	332.5
Gas Rate through Pump,	39.6	6.7	N/A
Gas Rate from Casing,	76.9	13.1	N/A
Total Gas Rate,	N/A	N/A	41.0
Free Gas Percent, %:	6.6	1.3	N/A
Water Rate,	131.9	131.4	129.3
Total Rate,	519.6	480.6	461.7
Pumping Pressure,	440.4	2261.7	115.0

Pct Free Gas Avail at Pump, %:	17.1
Natural Gas Separation, %:	15.0
Pct Free Gas into Pump, %:	6.6
Gas Separator Installed?:	Yes
Gas Separator Efficiency, %:	60.0

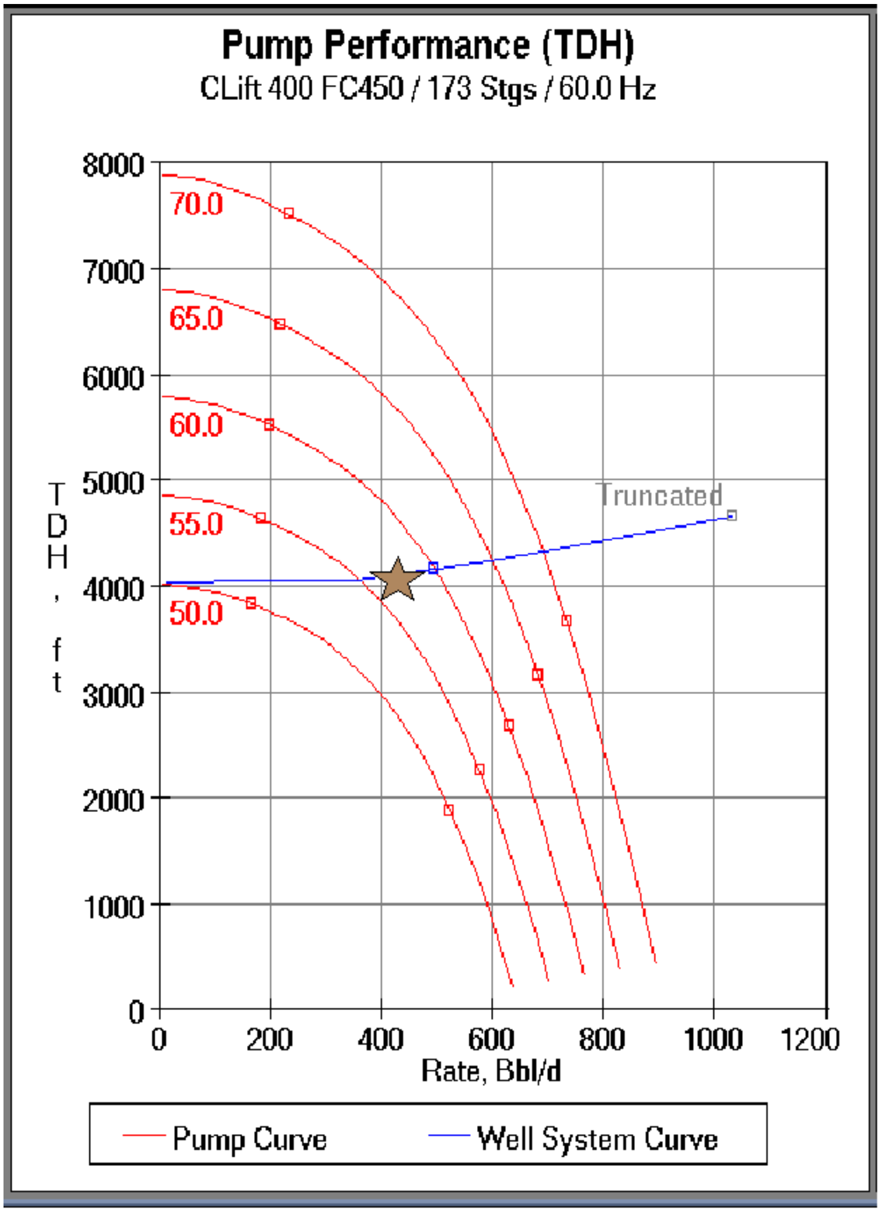
Performance of the SMI-130 A7 system using SubPump

SubPump can give the load on the motor too.

```
Manufacturer: CLift
                            Series: 562
                              Type: KMB - Single
        Name Plate Power,       HP:     50.0
      Name Plate Voltage,    Volts:     1250
      Name Plate Current,     Amps:     24.0
    Name Plate Frequency,       Hz:       60
            Adjust for Motor Slip:       Yes
     Operating Frequency,       Hz:     60.0
    Operating Motor Load,       HP:     33.6 (@ Operating
Frequency)
    Operating Motor Load,        %:     67.2
         Operating Speed,      RPM:     3526
       Operating Current,     Amps:     17.4
       Operating Voltage,    Volts:     1250
  Operating Power Factor,     frac:    0.804
    Operating Efficiency,        %:     86.1
          Fluid Velocity,   ft/sec:      0.7
```

The fluid velocity across the motor is a bit low.

ESP – Operation



You can perform surveillance on the system by plotting the operating point versus the pump curve at the frequency of operation. Be sure to correct the surface rates to downhole conditions first.

Use the ratio of surface to downhole rates in SubPump's reports to correct the measured surface rates to estimated downhole rates.

Use the system curve to find the TDH.

Deviations from the curve indicate pump wear or other inefficiencies.

10.1 ESP Operation Questions

If the horsepower increases the current

a. increases
b. decreases
c. stays the same if the rate is the same

The current is recorded by the _____________.

The current on an ESP is running at 30 amps. The underload should be set at

a. 10 amps
b. 26 amps
c. 33 amps
d. 40 amps

Restart is sometimes allowed on

a. overload
b. underload
c. never allowed

Underload is *not* caused by (may be more than one answer)

a. closing the surface valve
b. shutting in the well
c. heavy fluids in the pump
d. gas in the pump
e. tubing leak
f. debris in the pump

ESP Operation Questions

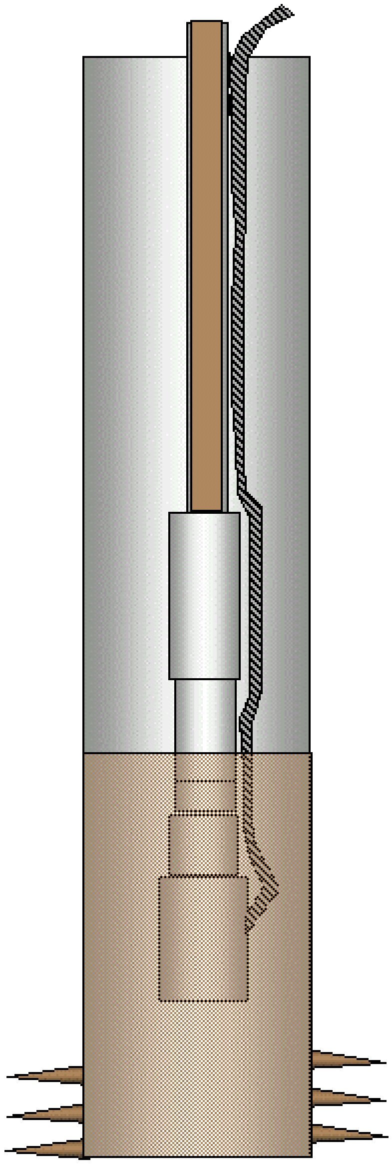
Name 3 things to record every day from the ESP operation:

When the pump first begins to turn after being switched on, the pump (with no check valve) sees

a. high head, low rate
b. low head, high rate
c. low head, low rate
d. high head, high rate

Starting current is ____ times normal operating current
a. 1.0
b. 0.5
c. 1.1
d. 3

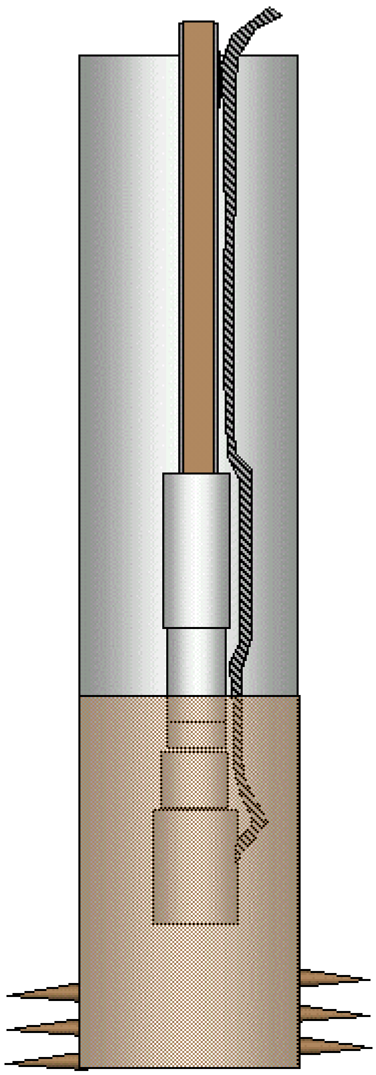
11 ESP - What *not* to do to an ESP



Design

• Don't use an ESP when other lift (e.g. gas lift) is more appropriate. Pumps don't like gas or sand.
• Don't ignore the forecasted pressures, GORs, water-cuts
• Don't forget about proper motor cooling. Flow from the zone past the motor is the only cooling available. Check that the design fluid velocity is > 1 ft/sec.
• Although the pump can be installed through a dogleg (<~3^{o}/100'), don't forget that the ESP needs to be installed in a straight section of the hole.
• Include information from the previous pump operation in the new design. Where possible, include info from teardowns too.

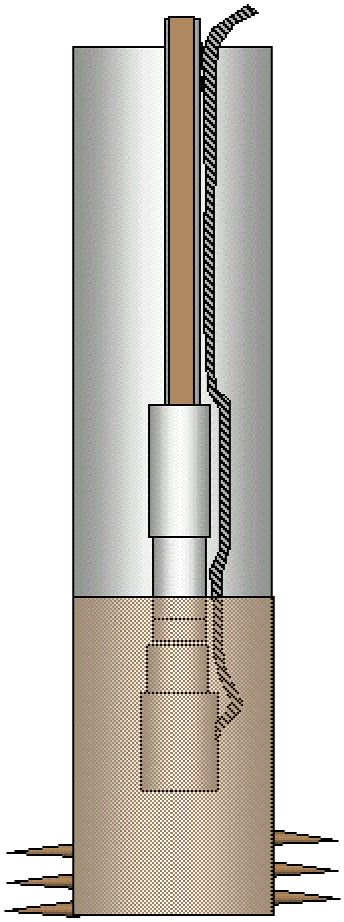
ESP - What *not* to do to an ESP



Installation

- Don't treat the ESP like a drill collar. Its one of the more fragile pieces of oilfield equipment.
- Don't let the ESP components bend. Proper support of the assemblies (to keep them from bending when laid horizontally) is critical.
- Don't forget to use proper procedures when performing the installation. See API RP 11S3.
- Don't let the pump run backwards. Check the performance and if in doubt, reverse the motor leads and check the performance again.

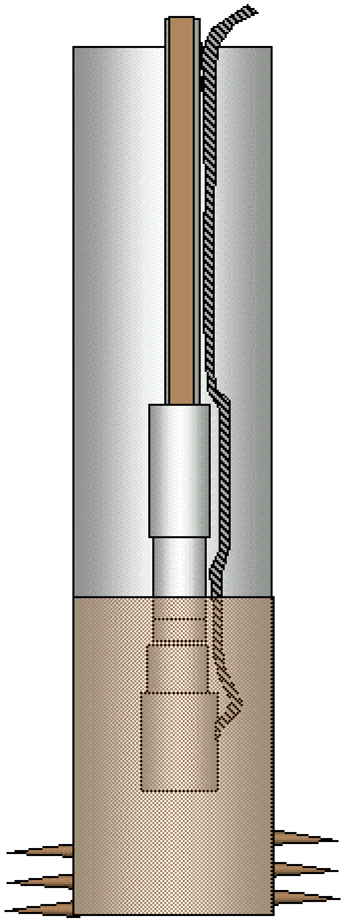
ESP - What *not* to do to an ESP



Operation

• Don’t let much gas into the pump.
• Don’t restart the pump too much.
• Don’t restart the pump too fast.
• Don’t let the pressure off of the annulus too fast.
• Don’t ignore the pump.
• Follow API RP 11S procedures for monitoring, maintenance and troubleshooting.
• Check the operating point of the pump on the pump curve. (can use SubPump software).

12 ESP - More Information



Further Reference

PEGS G-10641.03 Electric Submersible Pumping, 8/91 (Shell Oil)
API 11S, Recommeded Practice for the Operation, Maintenance and Troubleshooting of ESP Installations, 1/94
API 11S2, Recommeded Practice for ESP Testing, 1/90
API 11S3, Recommended Practice for ESP Installations, 5/93 (new revision imminent)
API 11S4, Recommended Practice for Sizing and Selection of ESP Installations, 5/93
Artificial Lift Manual, Part 2B, ESP Design Guide, SIEP EP94-2703, 2/95.
Centrilift Submersible Pump Handbook, 1987.