Session 17 –
"Ten of the Best – Ten of the most important extracts from previous sessions revisited"

We have now been presenting these Short Courses for a year and covered a huge amount of material!
Now is an appropriate time to revisit the previous sessions and extract some of the most important, most critical aspects that we have covered in them.
Some of you may have missed some of the sessions and/or would benefit from a refresher.

Ten of the Best

1- System Curves

2- Pump Curves

3- Operating Bands & System Control

4- Hooked Curves

5- Steep Curves vs Flat Curves

6- Variable Speed

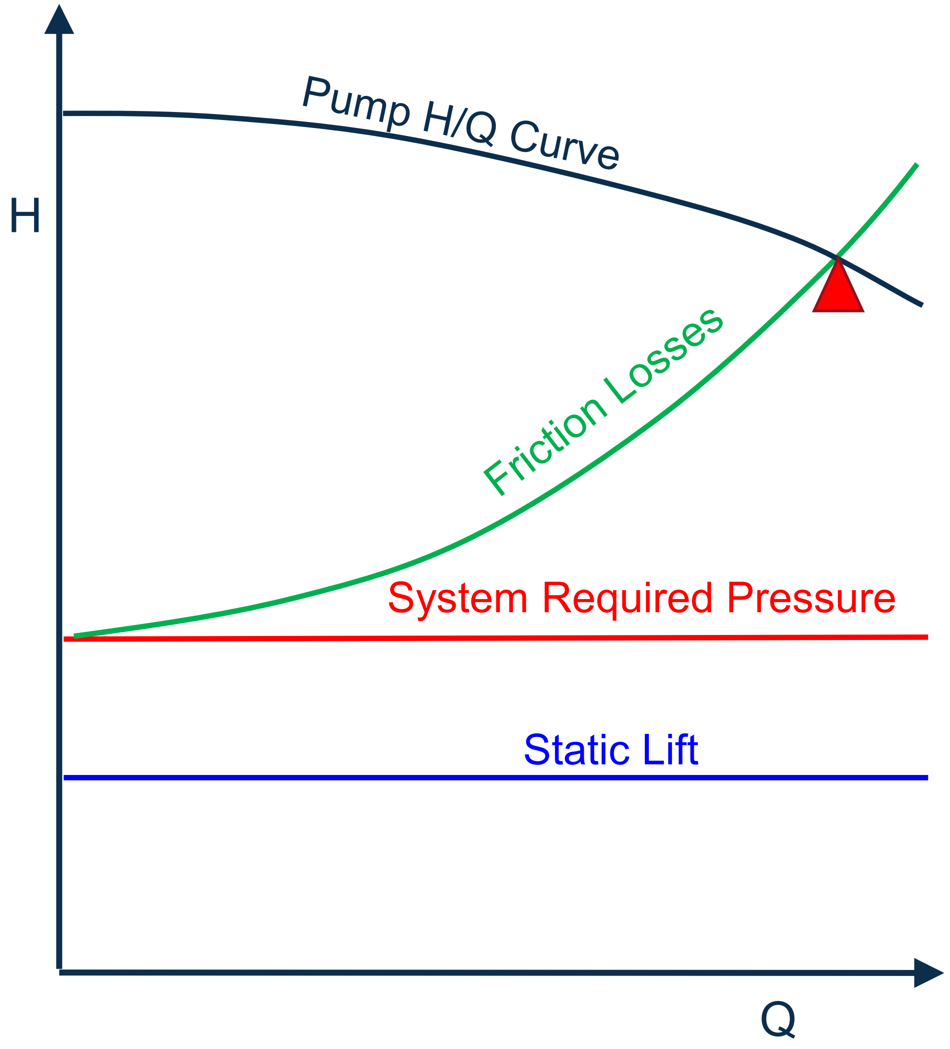
7- Parallel Operation

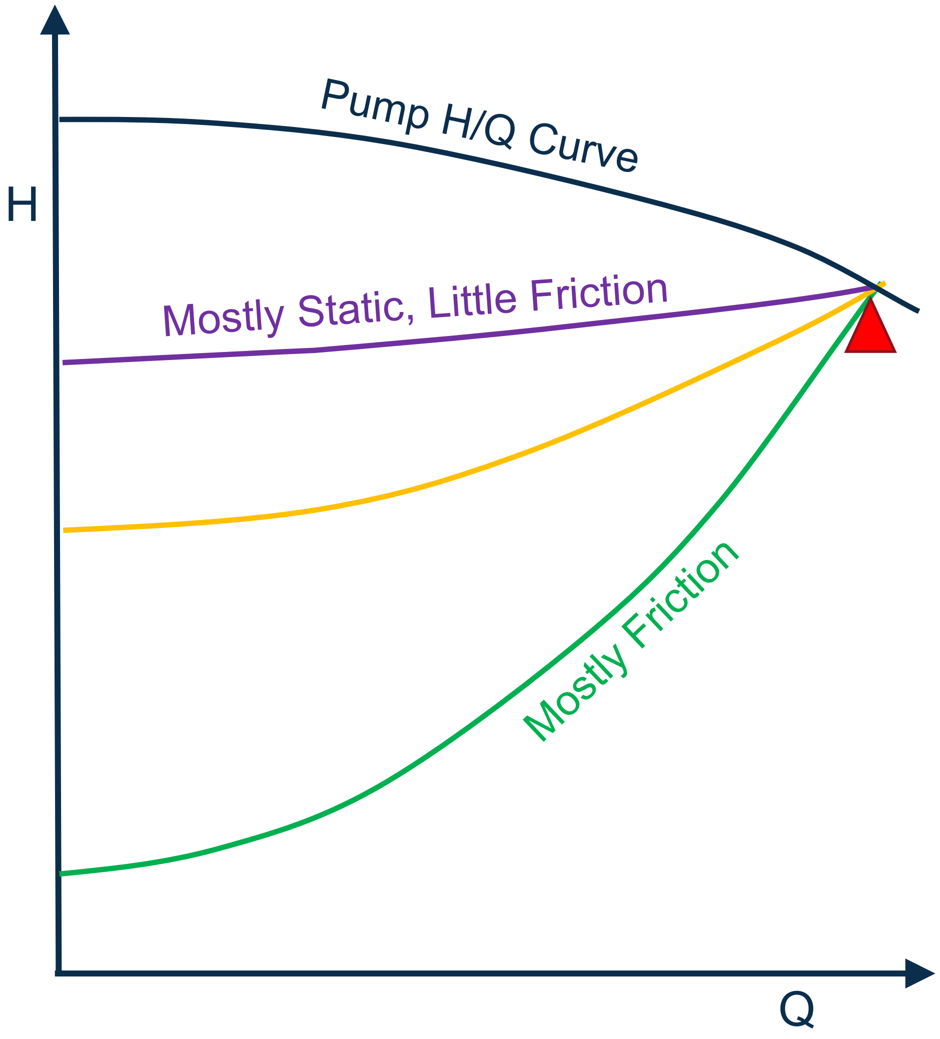
8- Series Operation

9- NPSHA, NPSHR & NPSH Testing

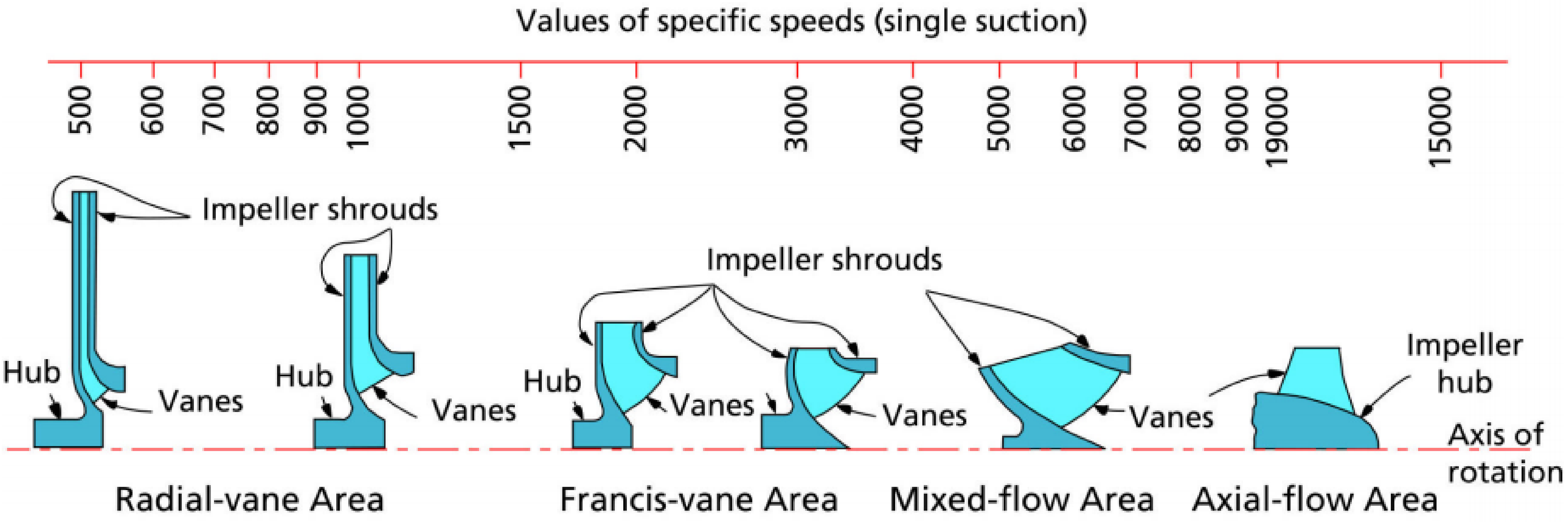
10- Three types of Cavitation

System Head Curve





Pump Curve Shape vs Specific Speed

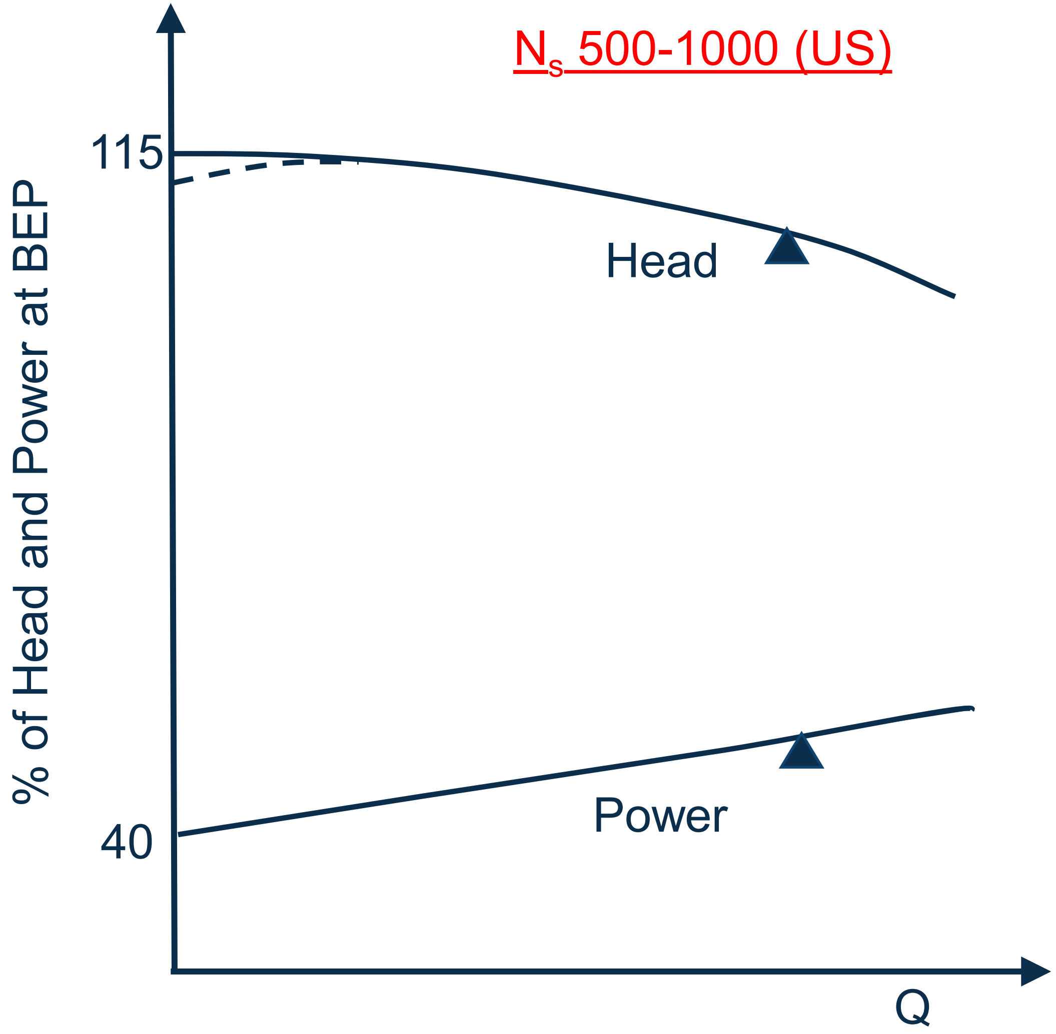


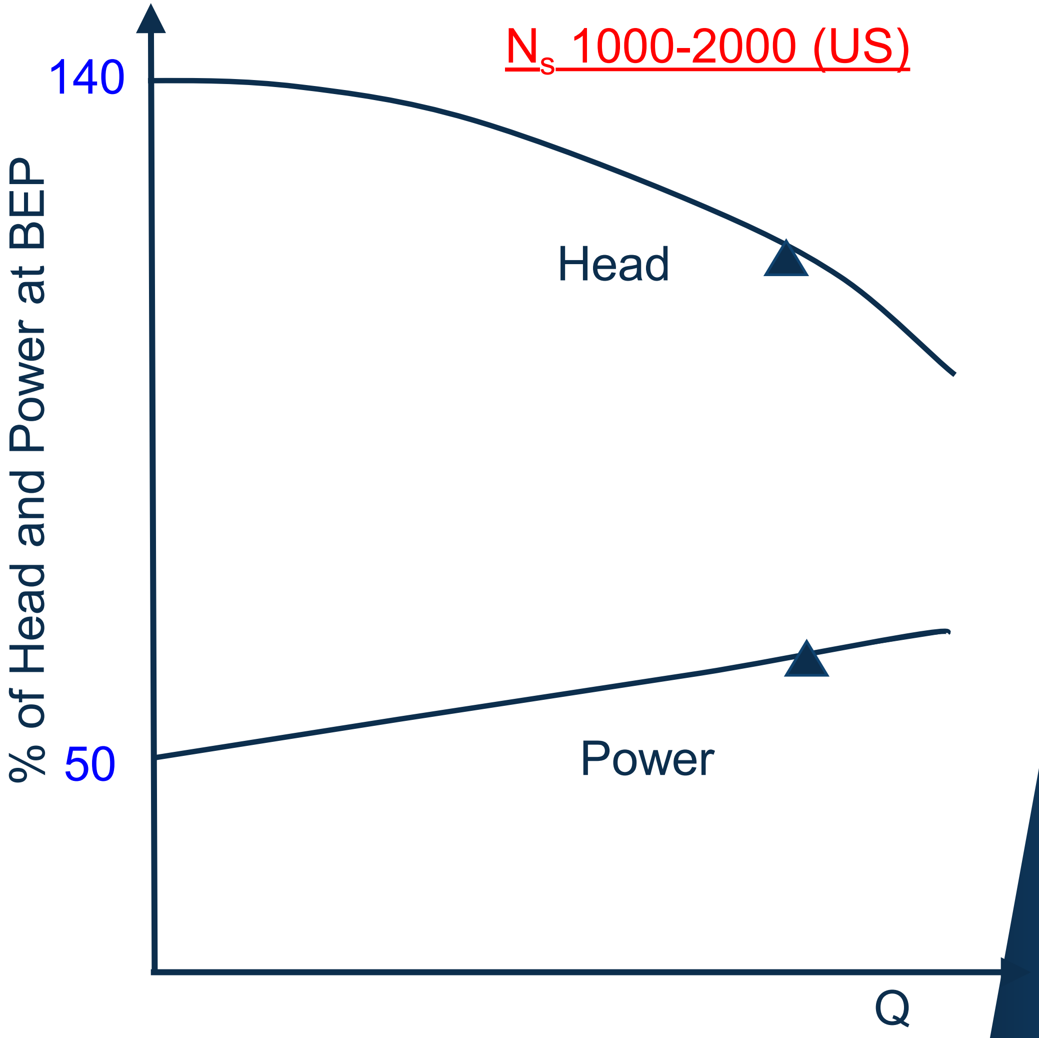
$N_S = N_{(RPM)}\, Q_{(BEP\ Full\ Dia)}^{\ 0.5} / H_{(BEP\ Full\ Dia)}^{\ 0.75}$

$N_{S(Metric)} = N_{S(US)} \times 1.16$ (m^3/hr, m, rpm)

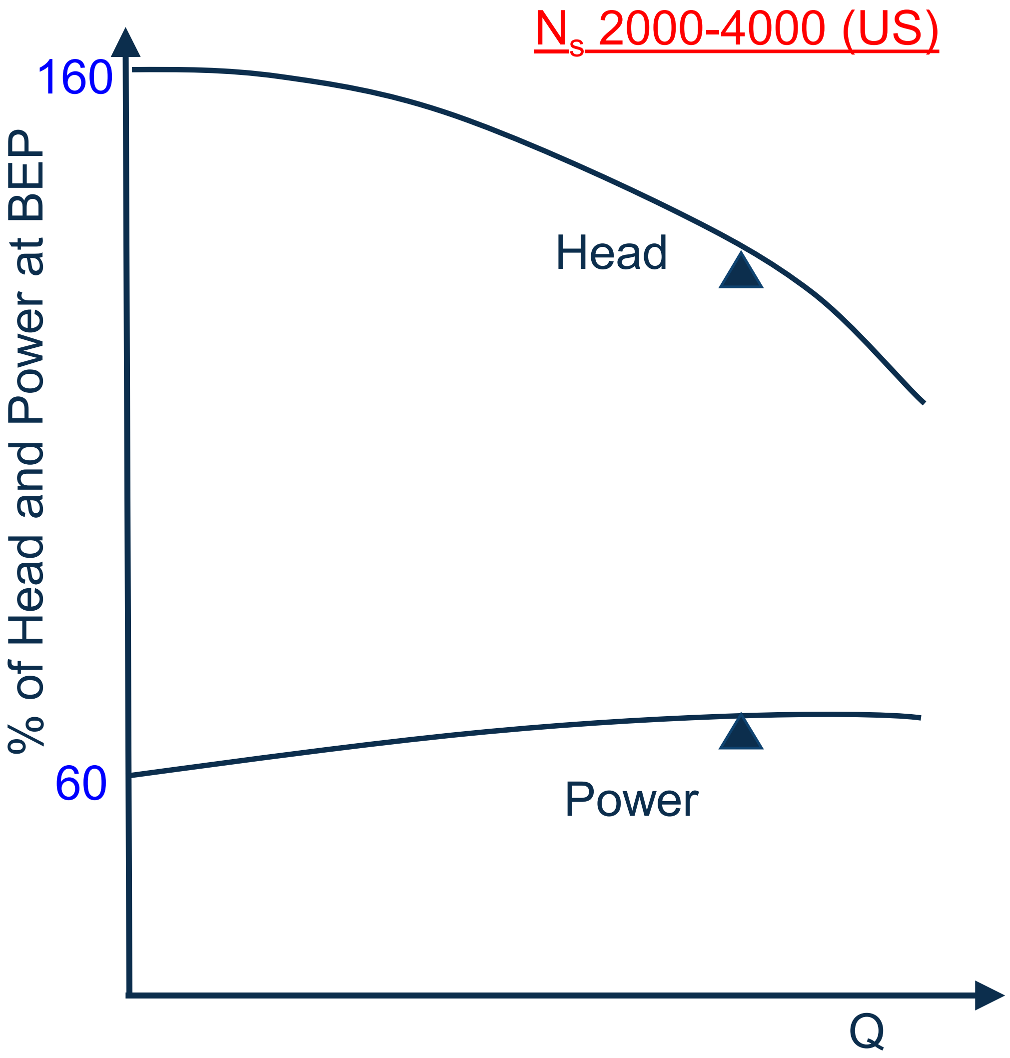
$N_{S(Metric)} = N_{S(US)} \times 0.02$ (m^3/s, m, rpm)

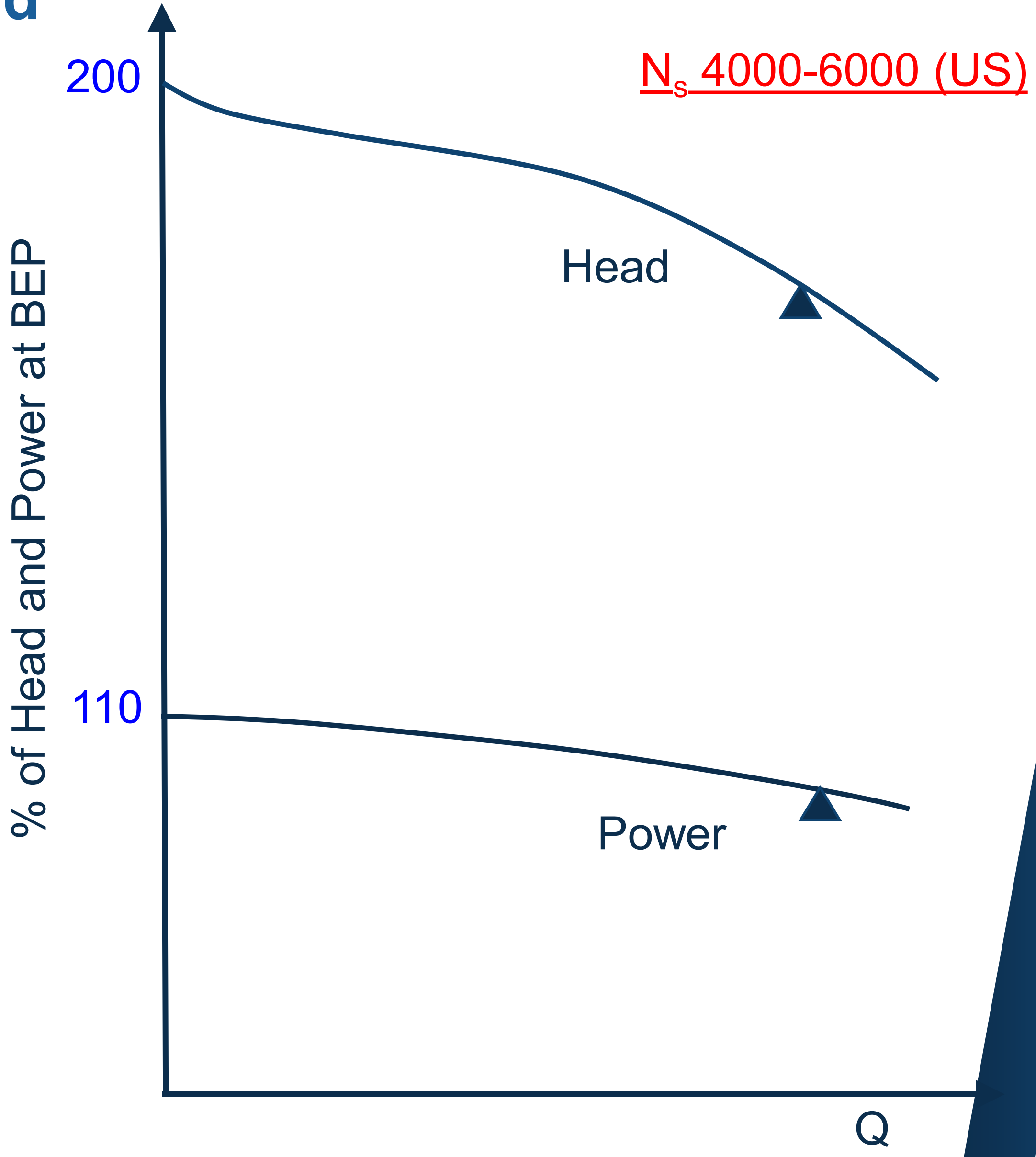
Pump Curve Shape vs Specific Speed



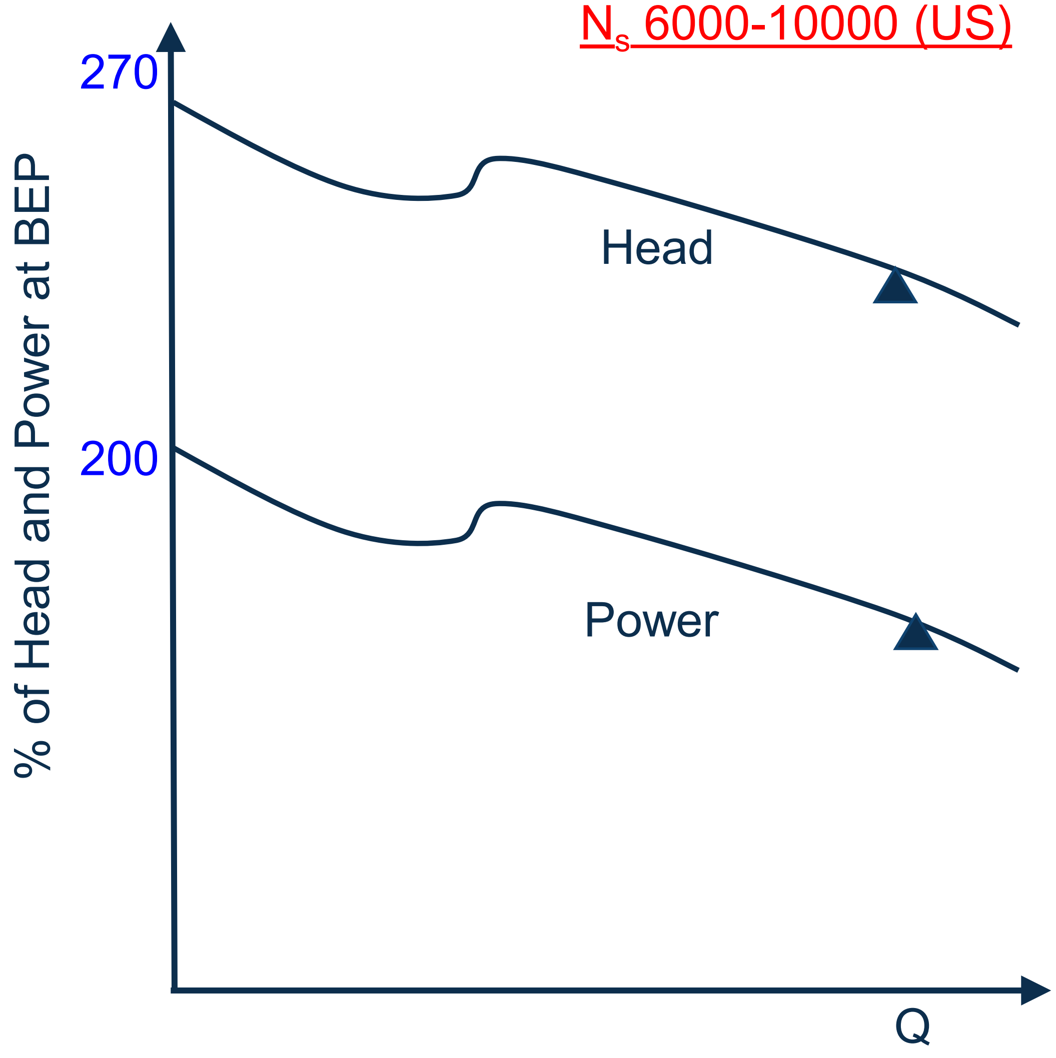


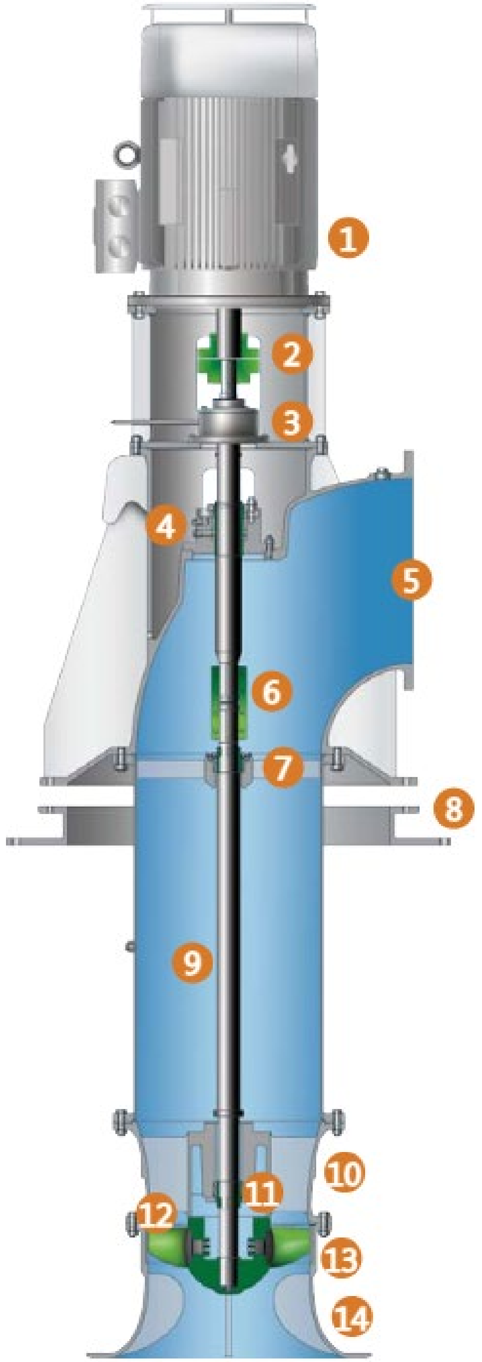
Pump Curve Shape vs Specific Speed





Pump Curve Shape vs Specific Speed





Operating Bands

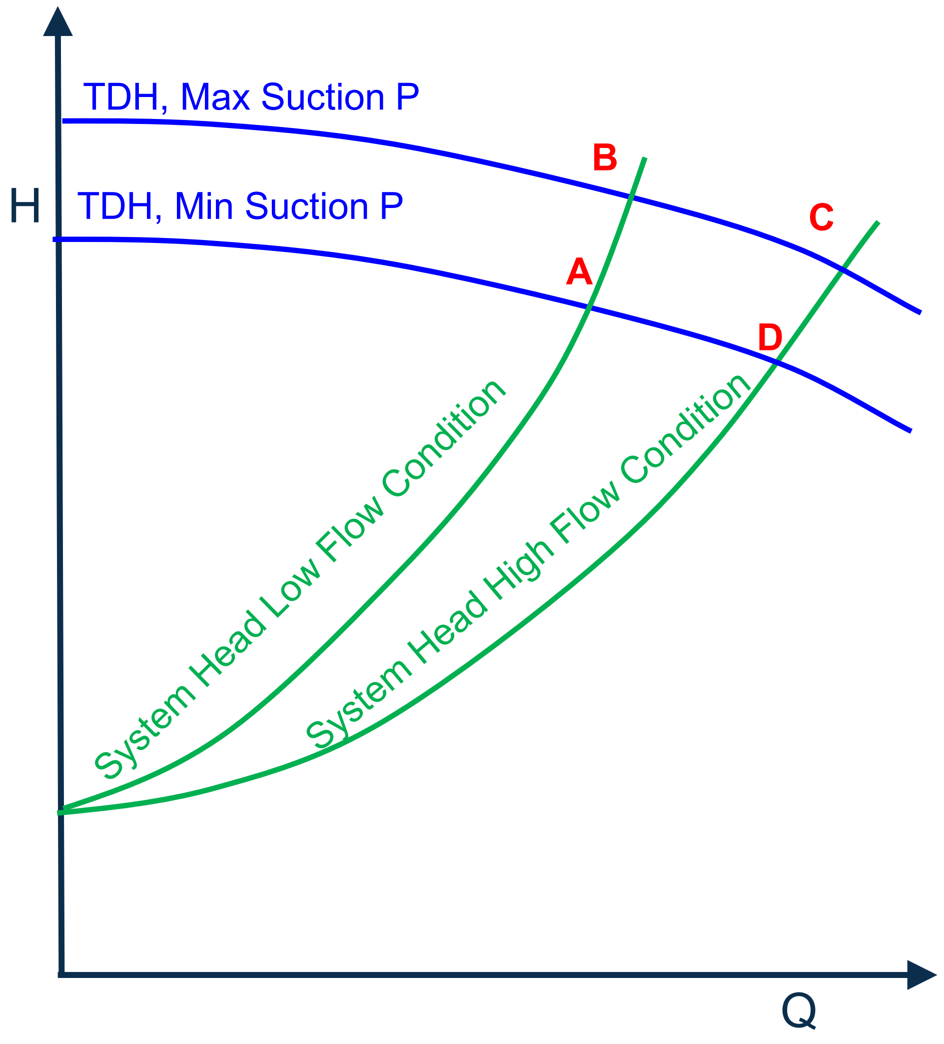
You will probably have a range of Suction Pressures and a range of Flow Rates to fulfill, and the pump might be asked to perform anywhere within the area A-B-C-D-A.

Condition D is probably the Rated Condition (worst case)

Some kind of system control will be required.

This might be

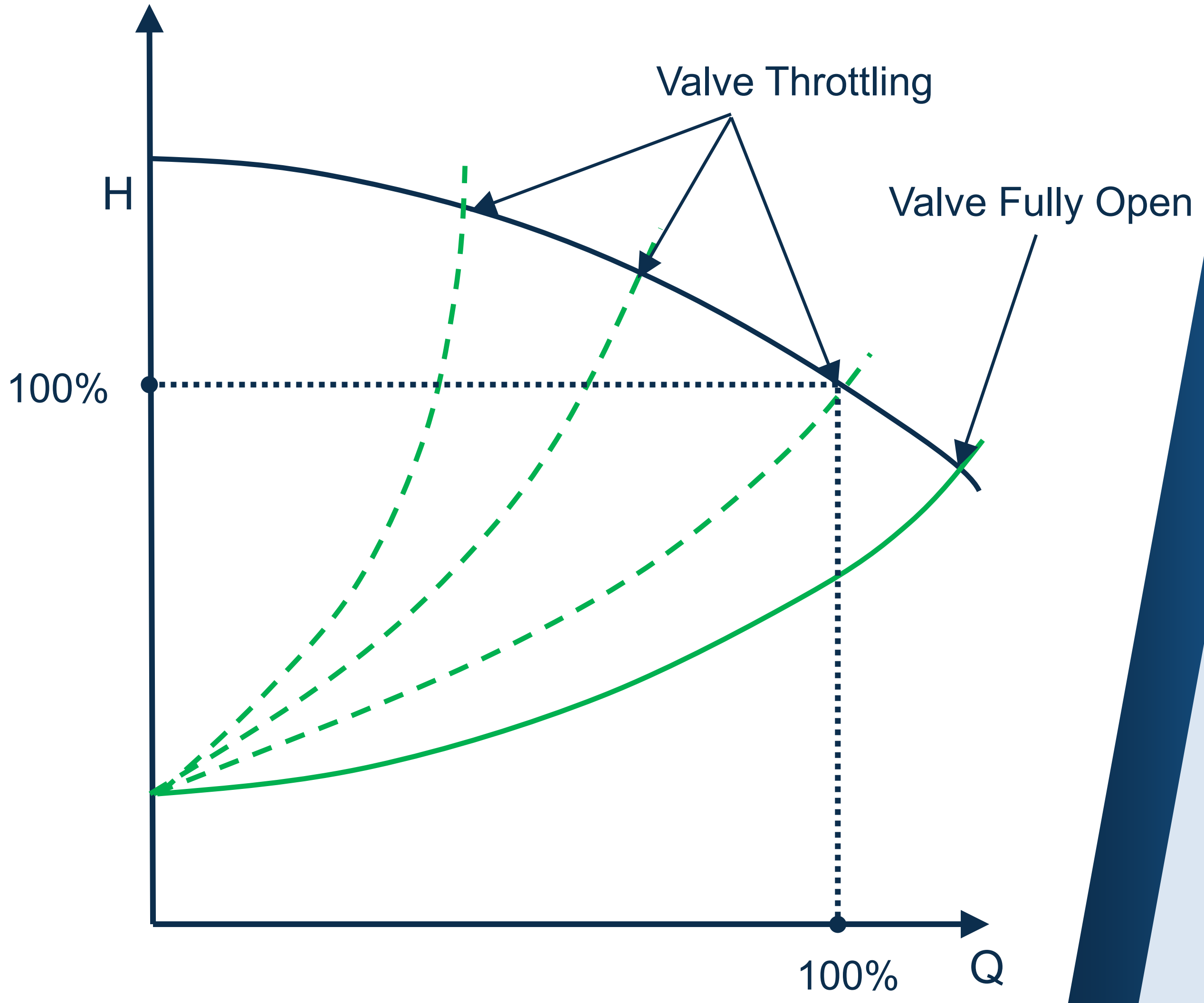
- Bypassing
- Valve Throttling
- Series or Parallel Pumping
- Variable Speed



System Control by Throttling

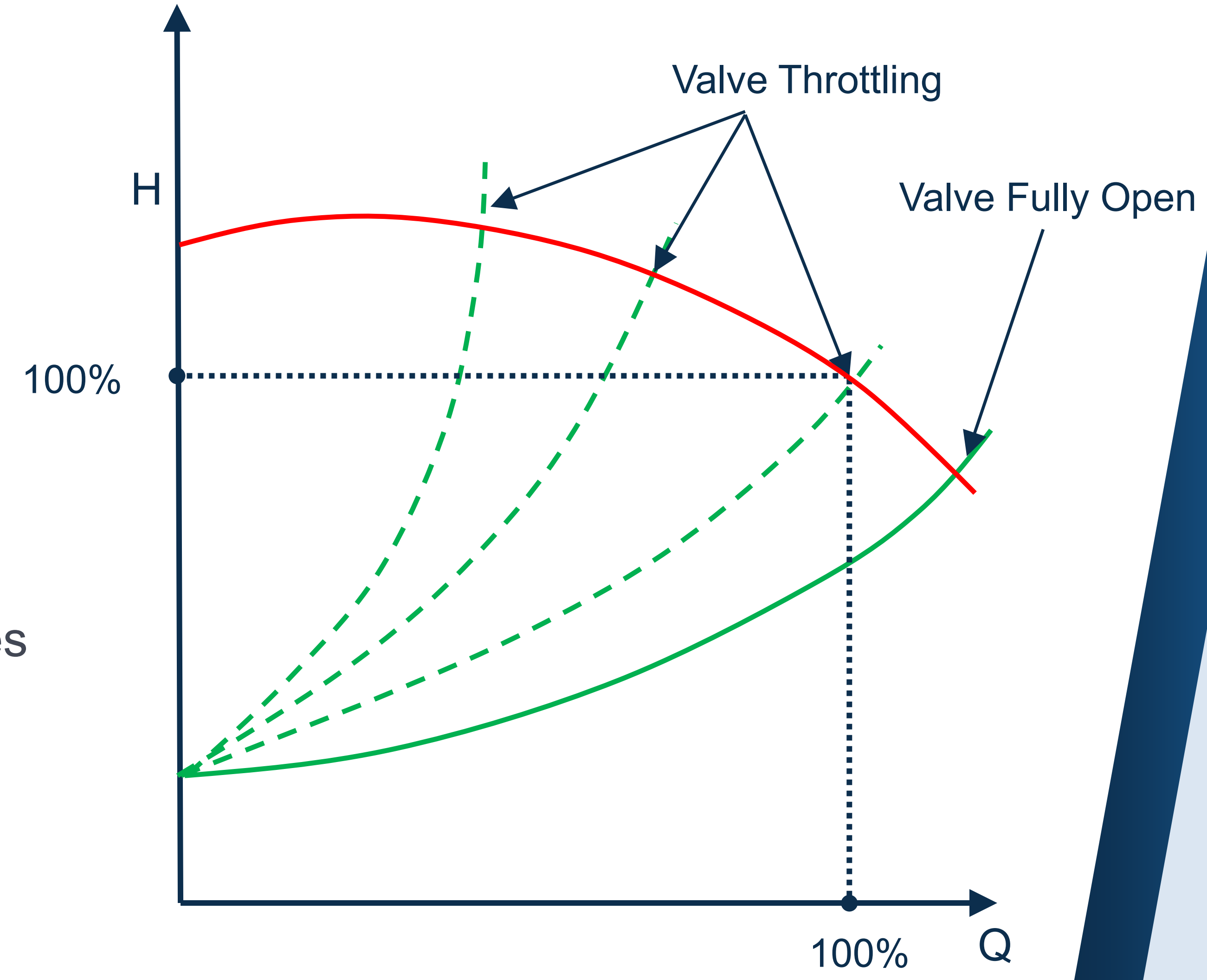
Probably the most common system control.

By opening or closing a control valve on the pump discharge, a “family” of system curves are created reflecting the ever-increasing frictional component of the system head.



System Control by Throttling – Hooked Curve (Gasp!)

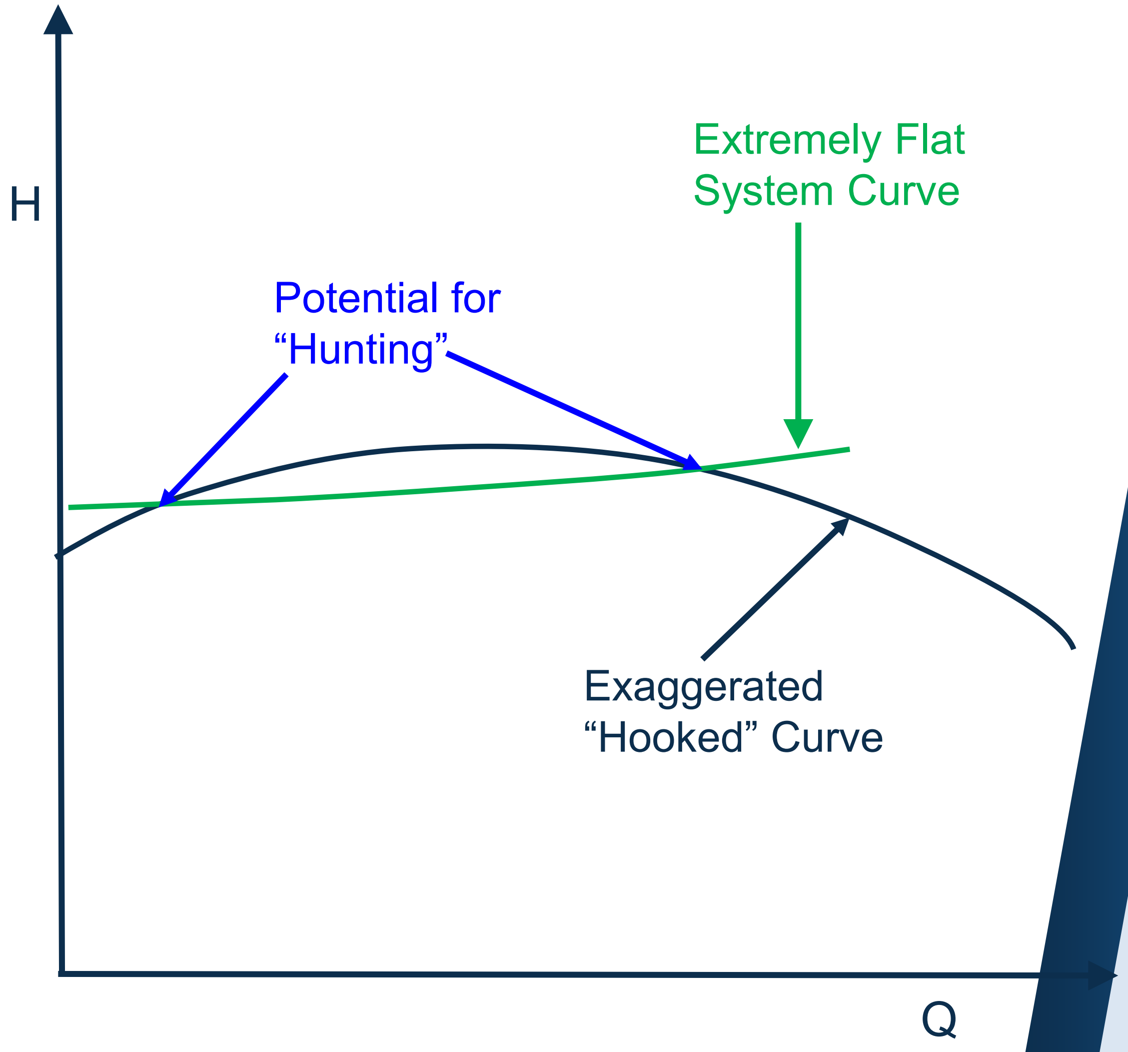
- Many specifiers run a mile from a hooked curve believing they are unstable.
- **A pump will only operate where the system permits – where the system curve crosses the pump curve.**
- **"The pump is slave to the system" ***
- Even as the control valve is gradually closed, each system curve only crosses the pump curve once.
- So no "hunting" is possible



* Simon Bradshaw

System Control by Throttling – Hooked Curve (Gasp!) Extreme Case

Only in the extremely rare case of an almost totally flat system curve (nearly all static head, very low frictional head) and a ***severely*** hooked curve might the system curve cross the pump curve more than once.

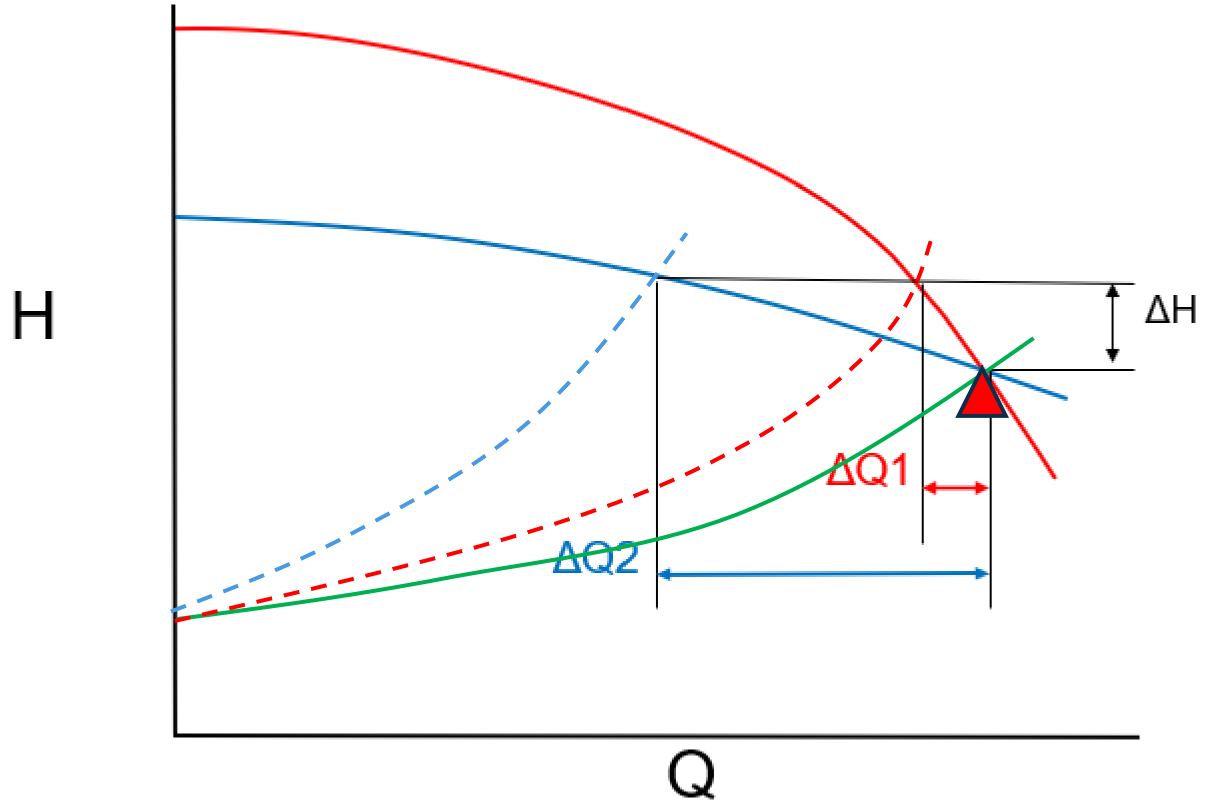


Steep or Flat Pump Curve?

- The question is “What do you want to achieve?”
- With a Flat pump curve **small** changes in System Head lead to **large** changes in Flow.
- With a steep pump curve **small** changes in System Head lead to **small** changes in Flow.

Impact of Curve Shape on Controllability

- A small change in Head (H) will have far less impact on the Flow Rate (Q) with a steep curve (red) than with a shallow curve (blue).



Variable Speed

<u>Affinity Laws</u>

Q1/Q2 = RPM1/RPM2

H1/H2 = $(RPM1/RPM2)^2$

Flow changes in DIRECT proportion to the speed change.

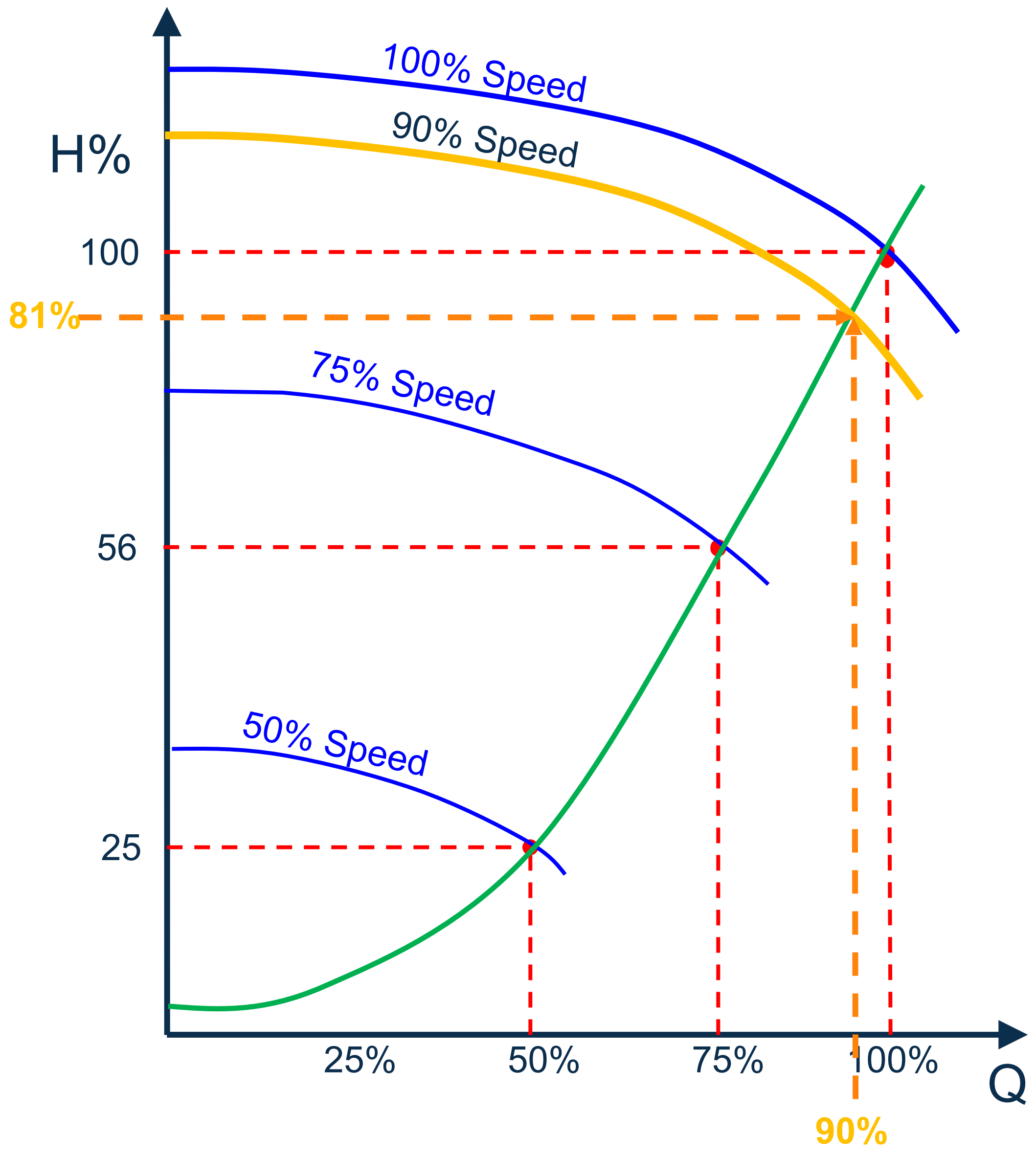
Developed Head changes by the SQUARE of the speed change.

So…reduce the speed to 90% of full

Flow reduces to 90% of full flow

TDH reduces to 81% of full head

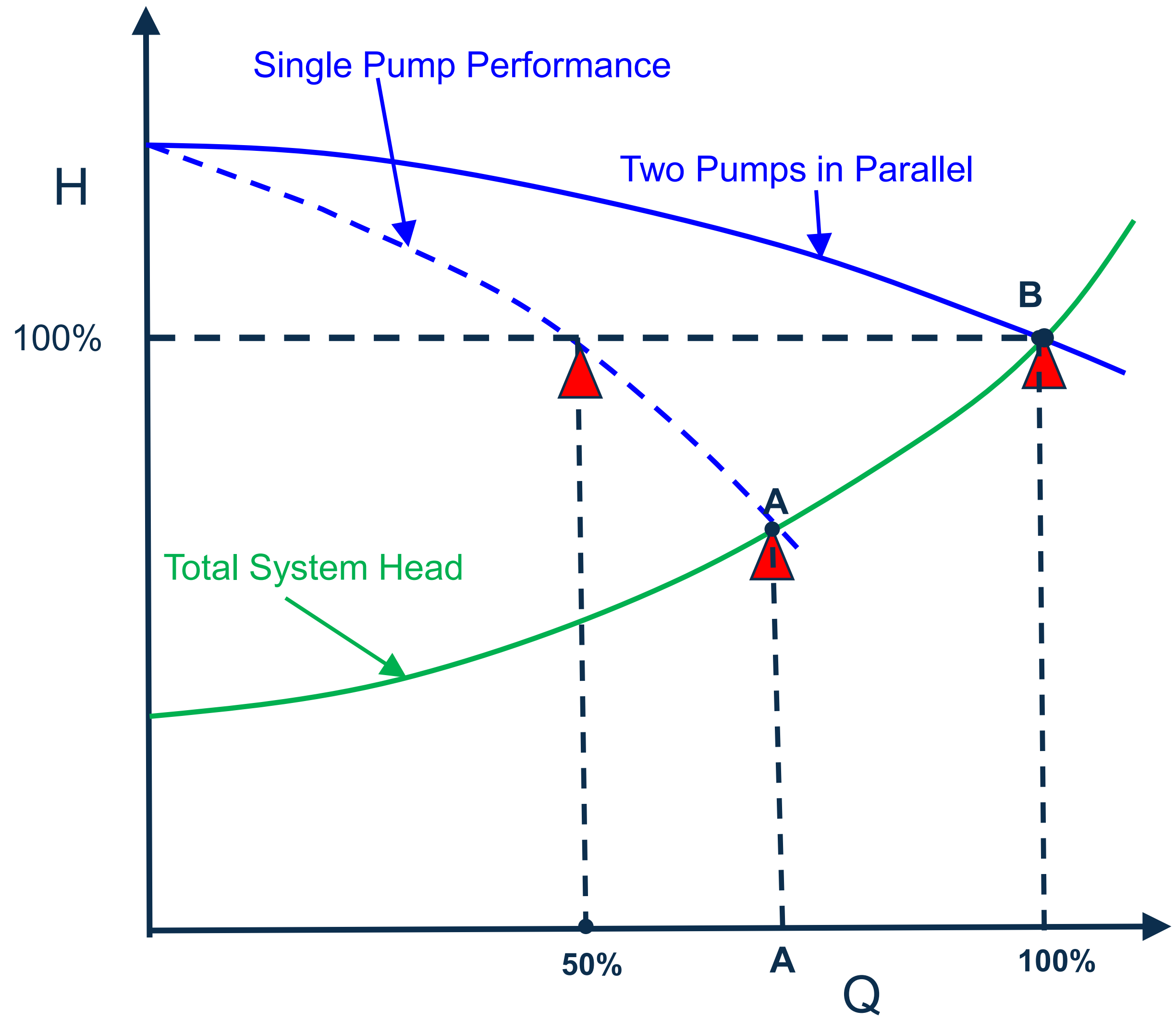
Variable Speed is not the "Cure-All" that many people expect!



Parallel Flow

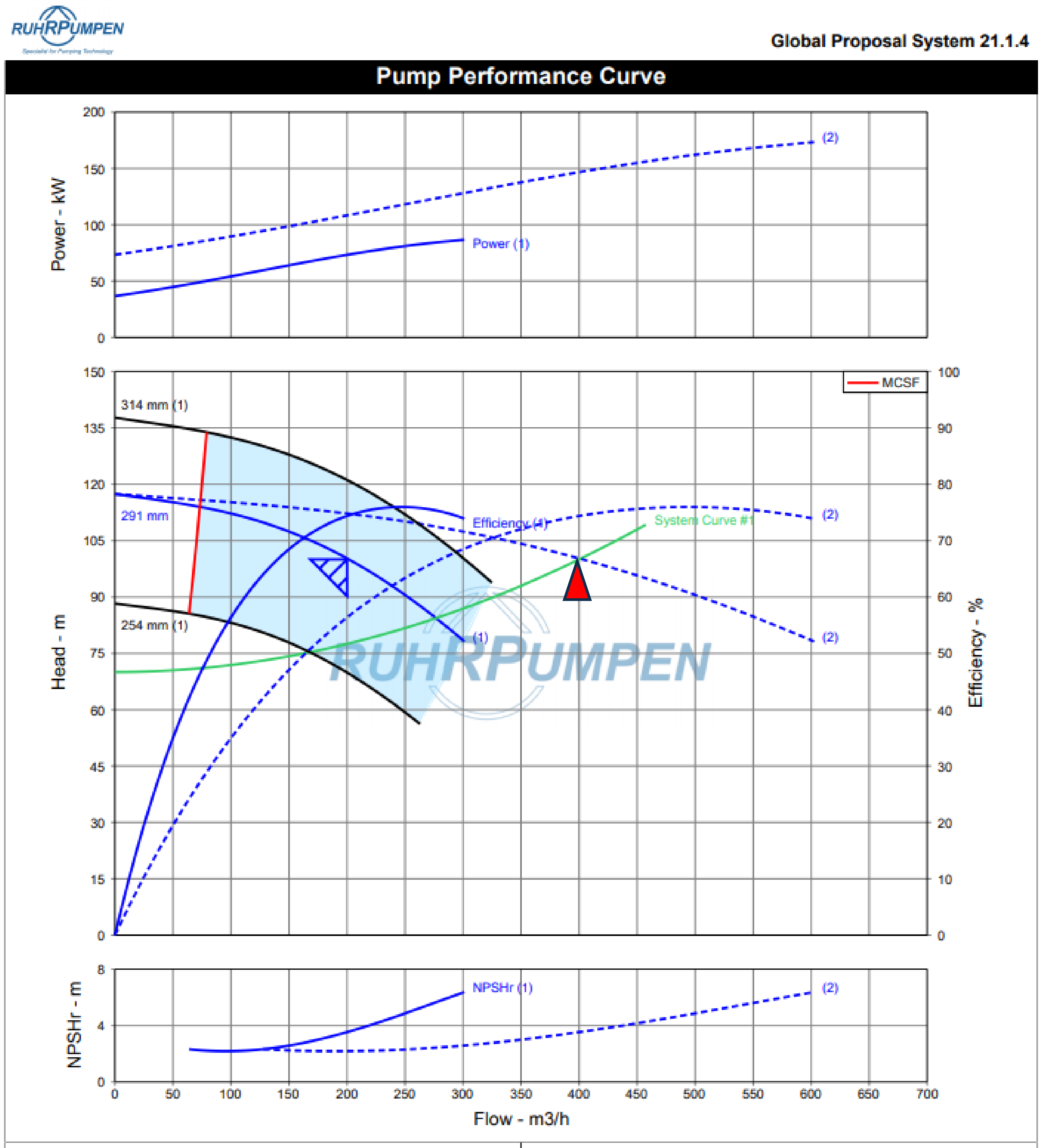
When operating in parallel, pumps will always develop an identical head value at whatever their equivalent flow rate is for that developed head, and the sum of their capacities will equal the system flow.

With one pump operating, system flow will occur at point A and with both pumps in operation, flow will occur at point B.



Parallel Flow

Typical manufacturer's curve with the system curve superimposed for parallel operation.



API610 12th & Parallel Flow

- *6.1.13 If parallel operation is specified and the pumps are not individually flow controlled, the following is required:*

  a) the pump head curves shall be continuously rising to shutoff;

  b) the head rise from rated point to shutoff shall be at least 10 %;

  c) the head values of the pumps at any given flow within the preferred operating range shall be within 3 % of each other for pumps larger than 3 in. (80 mm) discharge.

Here is why this is so important.

API Table 16 allows Performance Tolerances +/-3% at rated flow +/- 5%, 8% or 10% (depending on head) at shutoff.

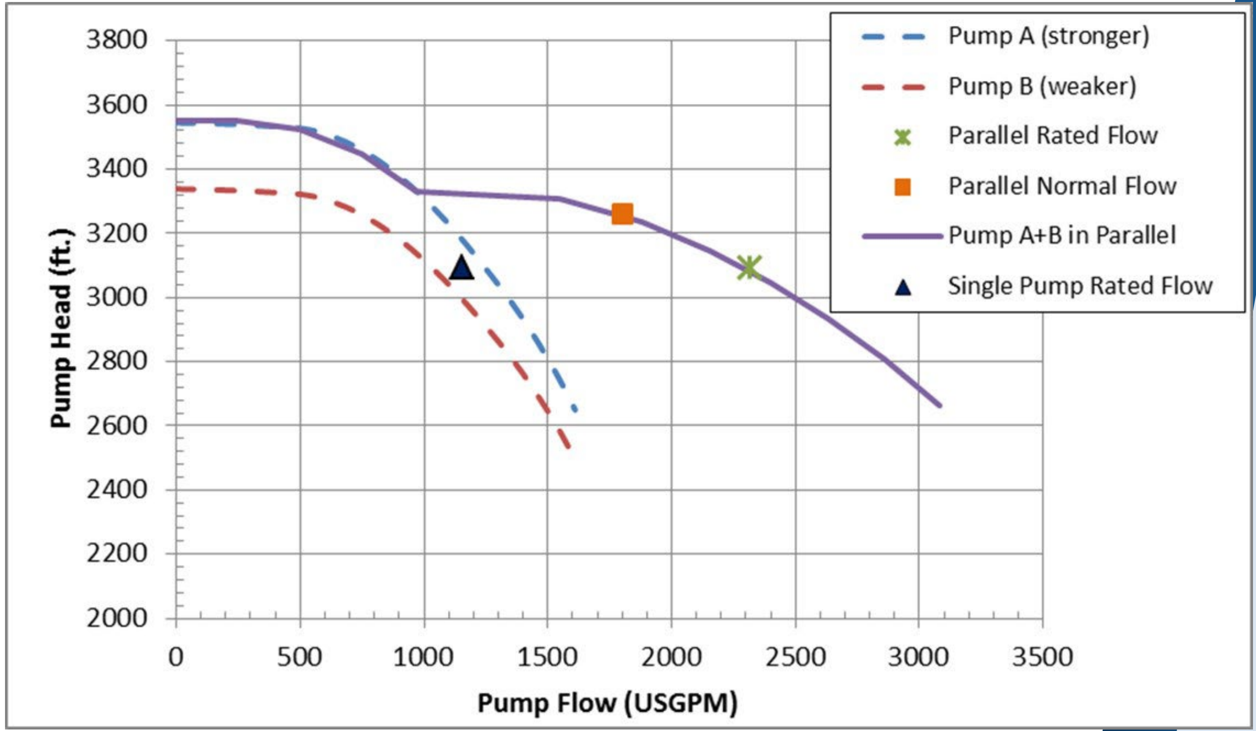
So without this change two “identical” pumps could easily have a “stronger pump” operating in parallel with a “weaker pump” as illustrated below.

API610 12th & Parallel Flow

The resulting combined Pump A+B parallel curve is discontinuous due to the mismatching of the two pumps. This exhibits itself as a step at around 1000 USGPM. (Below that point Pump B would operate at zero flow resulting in rapid failure).

In this scenario Pump A being stronger will force Pump B to operate back on its curve. If the system is operated at its Parallel Normal Flow, **Pump B will be running at around only 50% of BEP**. This is well outside the preferred operating range and will result in Pump B seeing higher wear and ultimately needing repair *much* sooner.

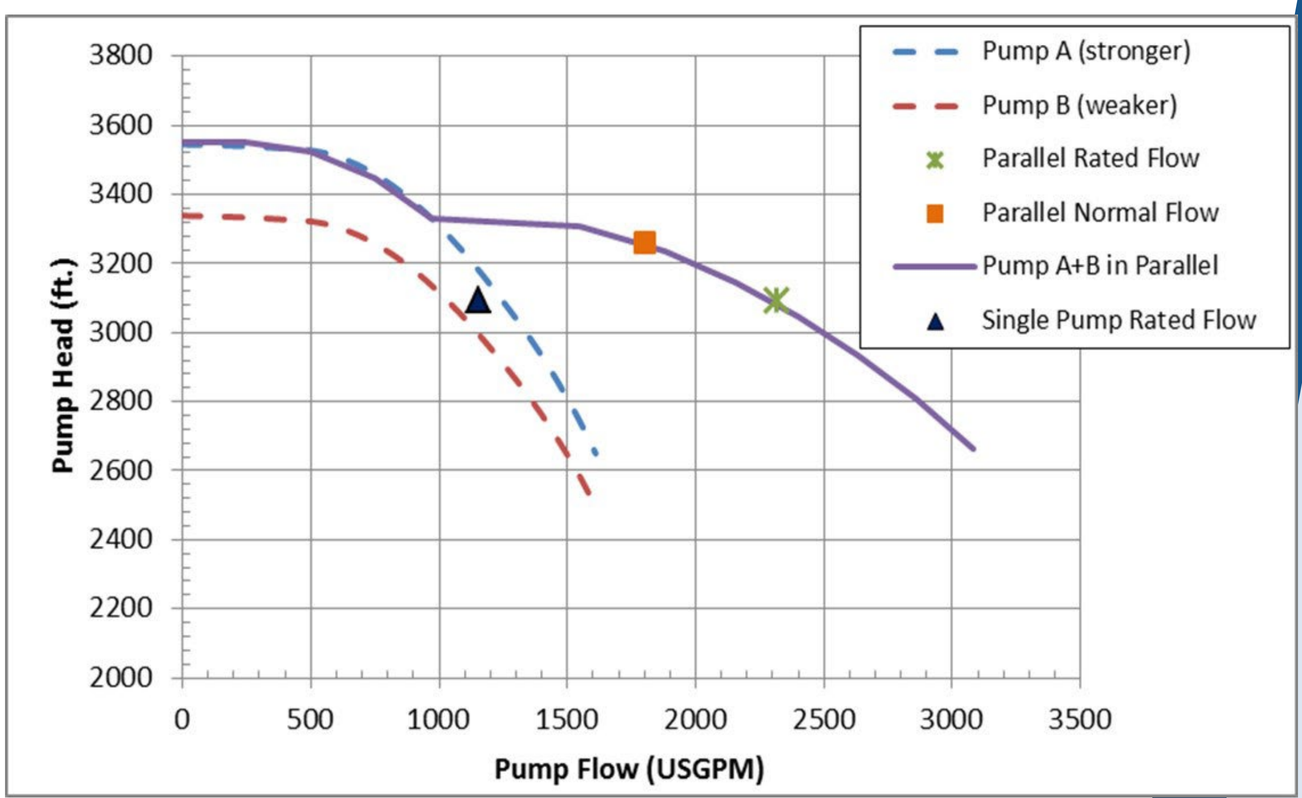
(Source – Simon Bradshaw, Director Engineering, CIRCOR)



Parallel Flow

Non-Identical Pumps in Parallel

Two non-identical pumps <u>can</u> still work in parallel but you will need to control the outlet stream of each pump independently. Otherwise one pump may well push the other out of its allowable operating range.

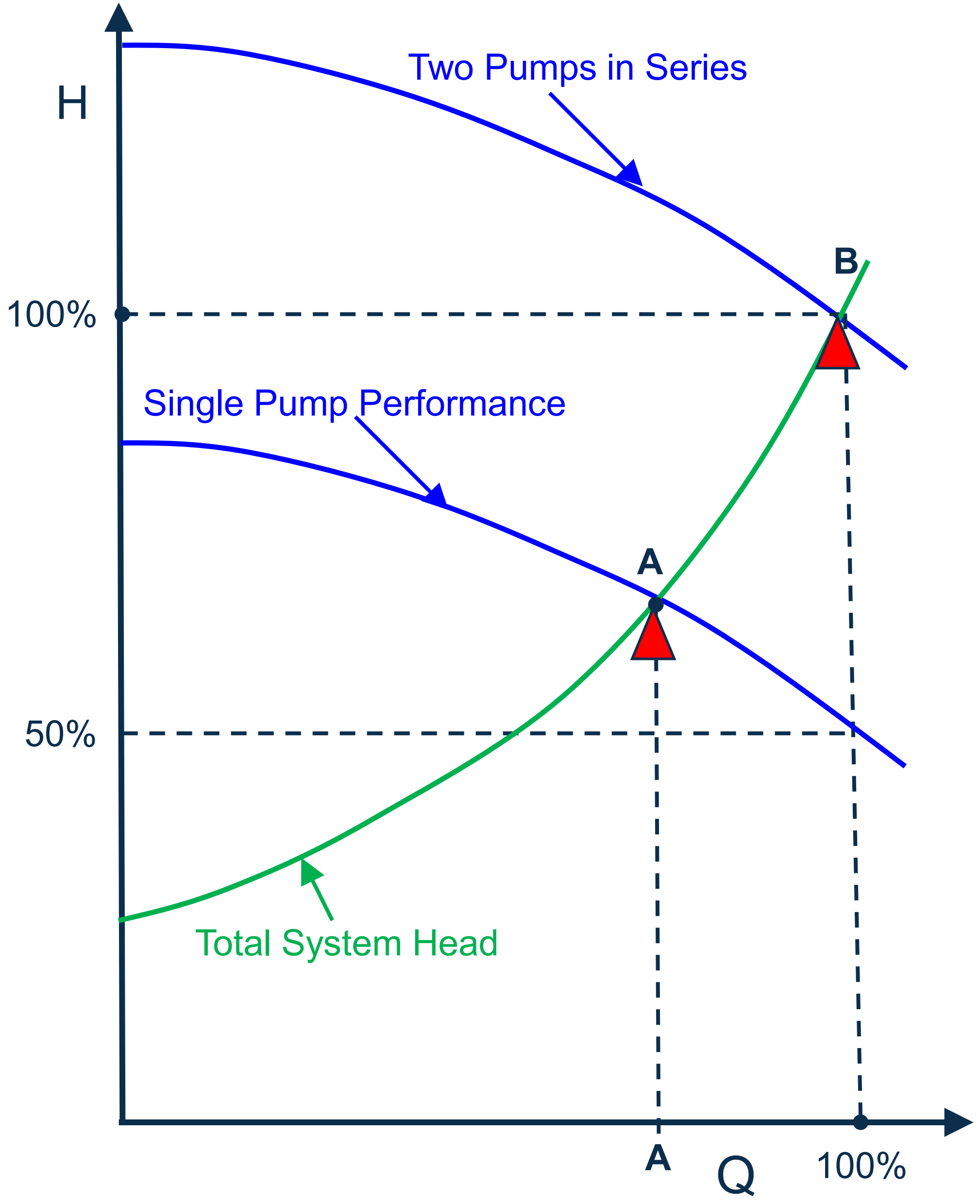


Series Flow

When operating in series, the total developed head will be the sum of the heads developed by each pump at any given flow.

Each pump must be selected to operate satisfactorily at the system design flow.

With one pump operating, system flow will occur at point A and with both pumps in operation, flow will occur at point B which is the System Design Flow



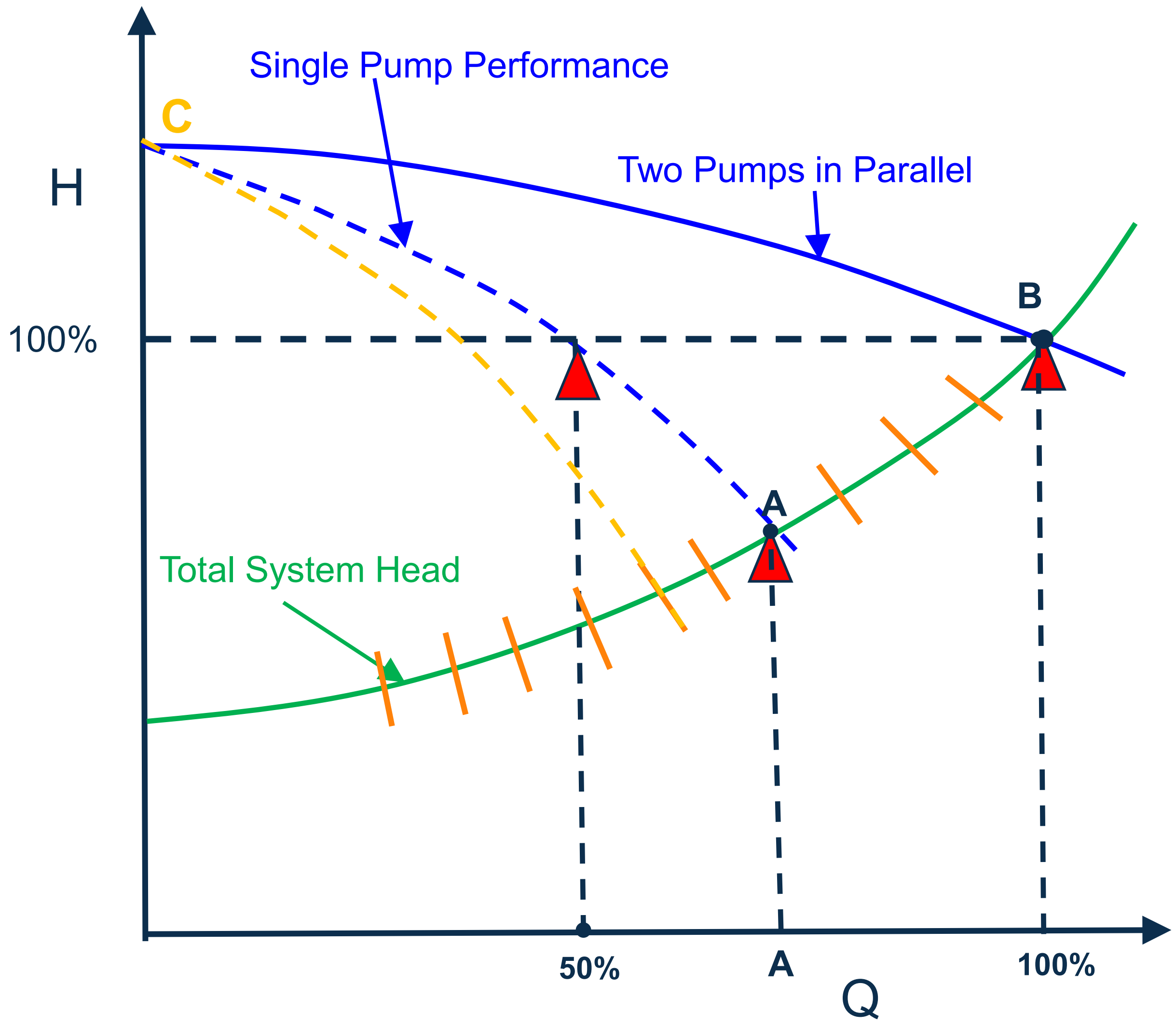
Parallel Flow with Variable Speed

With variable speed you have an infinite number of Pump Curves (partial curves illustrated in orange)

Typically you would start the lead pump under variable speed.

It would climb the system curve until it reached Point A at which point it is at full speed and would be locked at that speed.

The second (lag) pump would start under variable speed and continue to climb the system curve from Point A to Point B

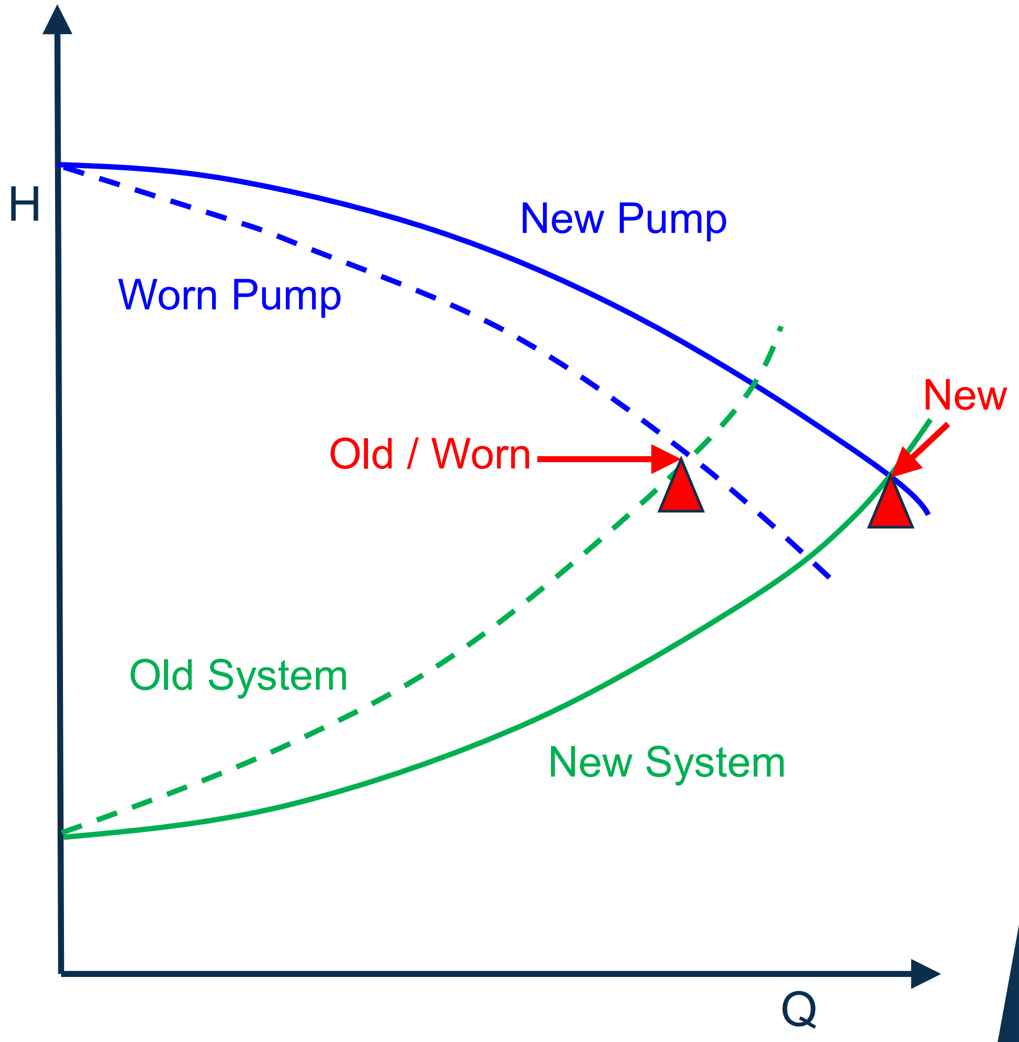


Old Age

(It comes to us all!)

A worn pump will see its performance curve fall off as shown by the dashed line.

Similarly frictional resistance will increase in an aging system due to corrosion and scale build up.



$NPSH_A$

What it is.

At any given temperature, all liquids have a definite pressure at which they boil. Every day we witness the fact that a liquid boils at atmospheric pressure when it reaches a sufficiently high temperature. It is important to remember also that a liquid will boil at any temperature if the pressure is reduced sufficiently. While at sea level water boils at 100^0C (212^0F) at the top of Mount Everest it boils at 68^0C (154^0F)

It is the problem of the Process & Applications Engineers to make certain that there is enough pressure on the fluid being fed to the pump so that the liquid does not boil in the suction of the pump.

$NPSH_A$

Definition

Net

Positive (means head over and above the vapour pressure)

Suction (at the suction flange / centreline of impeller)

Head

Available

"The net positive suction head available is the total suction head in feet (meters) of liquid absolute determined at the suction flange minus the vapour pressure of the liquid in feet (meters) absolute"

NPSHA = Suction Pressure (ft or m) – Vapour Pressure (ft or m)

$NPSH_A$

Arithmetically:-

$$NPSHA = H_a - H_{vpa} +/- H_{st} – H_f$$

Where:-

H_a = the head from the absolute pressure acting on the surface of the liquid

(in an open suction system this will be atmospheric pressure, in a closed system it will be the pressure in the suction vessel acting on the surface of the liquid)

H_{vp} = the head from vapour pressure (always a negative value)

H_{st} = Static head above the pump impeller centerline (suction flange)

(this value is negative in the case of a suction lift)

H_f = Friction head in pipework (always a negative value)

$NPSH_{R\ (or\ 3\ or\ 1)}$

Definition

Net

Positive (means head over and above the vapour pressure)

Suction (at the suction flange / centreline of impeller)

Head

Required (historically by convention the same as $NPSH_3$)

$NPSH_3$ is measured and defined as a 3% reduction of pump TDH

$NPSH_1$ is measured and defined as a 1% reduction of pump TDH

"NPSHR is the total suction head in feet (meters) of liquid absolute measured at the suction flange / centreline of the impeller that corresponds to a 3% (sometimes 1%) reduction in discharge pressure."

$NPSH_R$ Why a Pump Requires a Positive Suction Head

A pressure drop occurs between the pump suction flange and the minimum pressure point within the pump impeller because of:

1- An increase in the velocity between the suction flange and entrance to the impeller vanes.

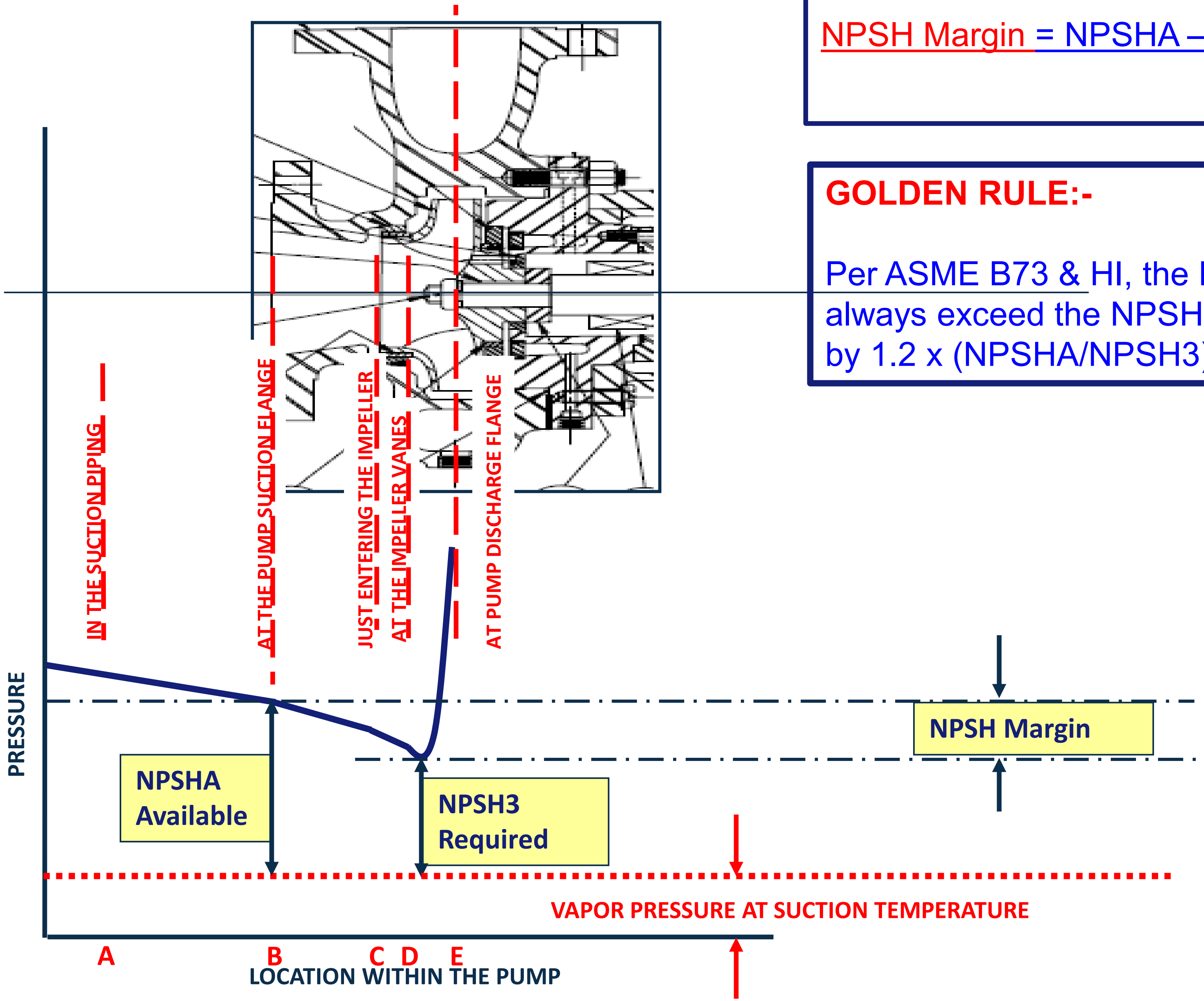
2- Friction & turbulence between the suction flange and the entrance to the impeller vanes

It is impossible to design a centrifugal pump in which there is no pressure drop between the suction flange and the entrance to the impeller vanes.

All pump systems must have a positive suction head sufficiently high to overcome this pressure drop within the pump and to keep the fluid from boiling at the pumping temperature.

$NPSH_R$

Visually



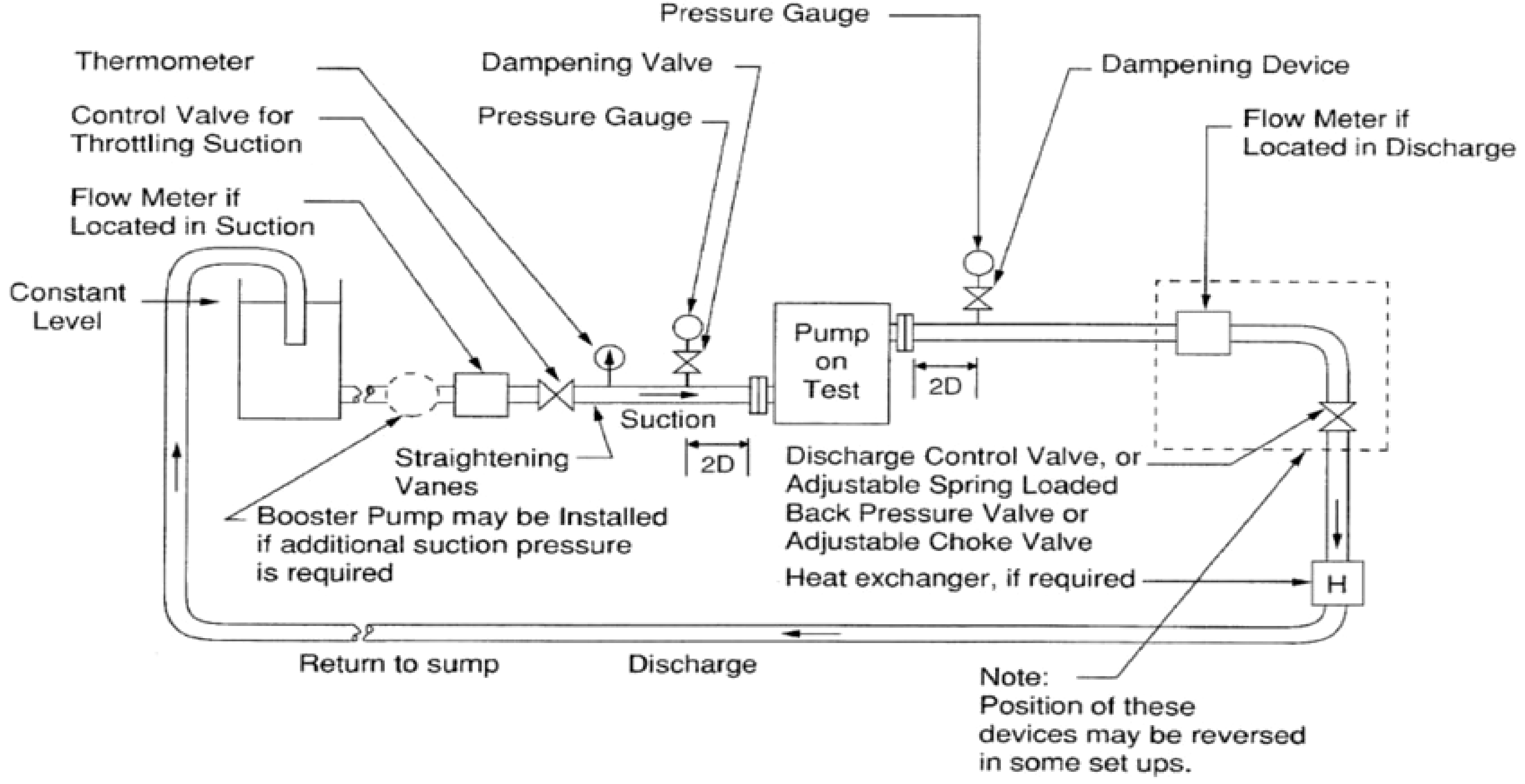
NPSH Margin = NPSHA – NPSH3.

GOLDEN RULE:-

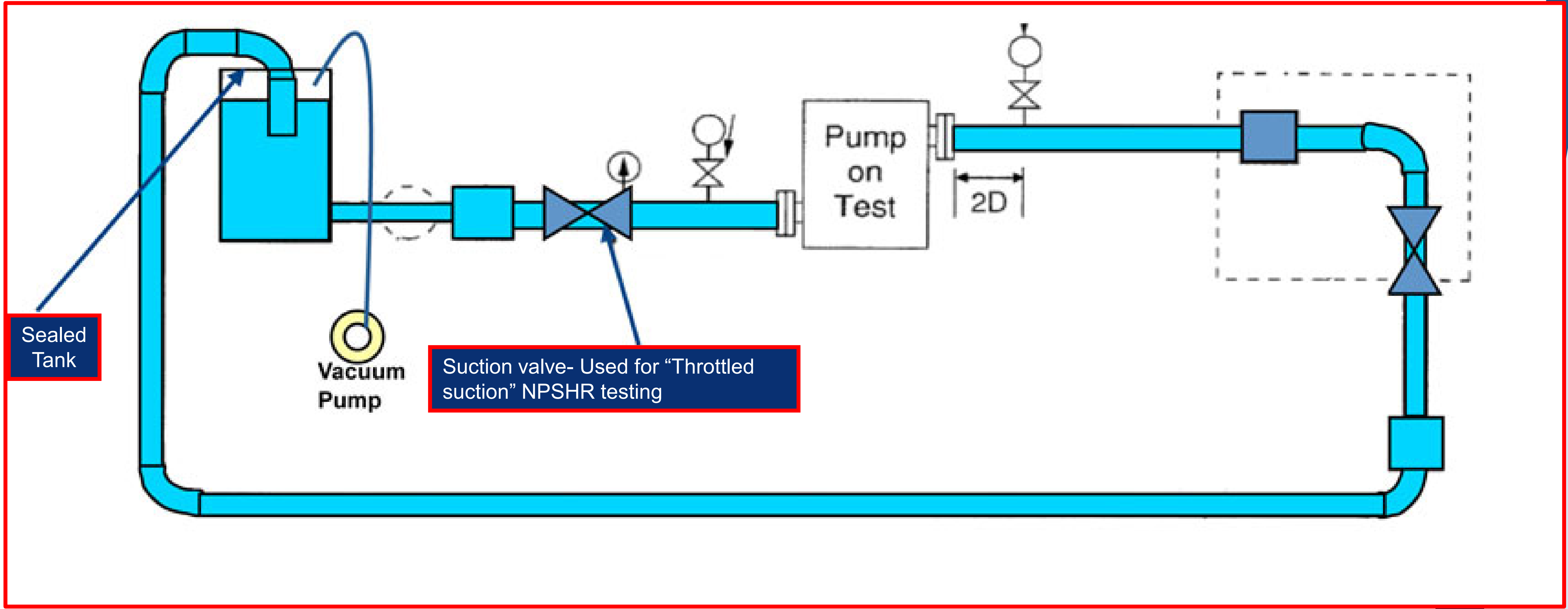
Per ASME B73 & HI, the NPSHA must always exceed the NPSH3, by 3Ft (1m) or by 1.2 x (NPSHA/NPSH3).

$NPSH_R$

Typical Pump Test Loop



$NPSH_R$ NPSHR Testing Procedure



$NPSH_R$ NPSHR Testing Procedure

- The pump is set to the rated speed.

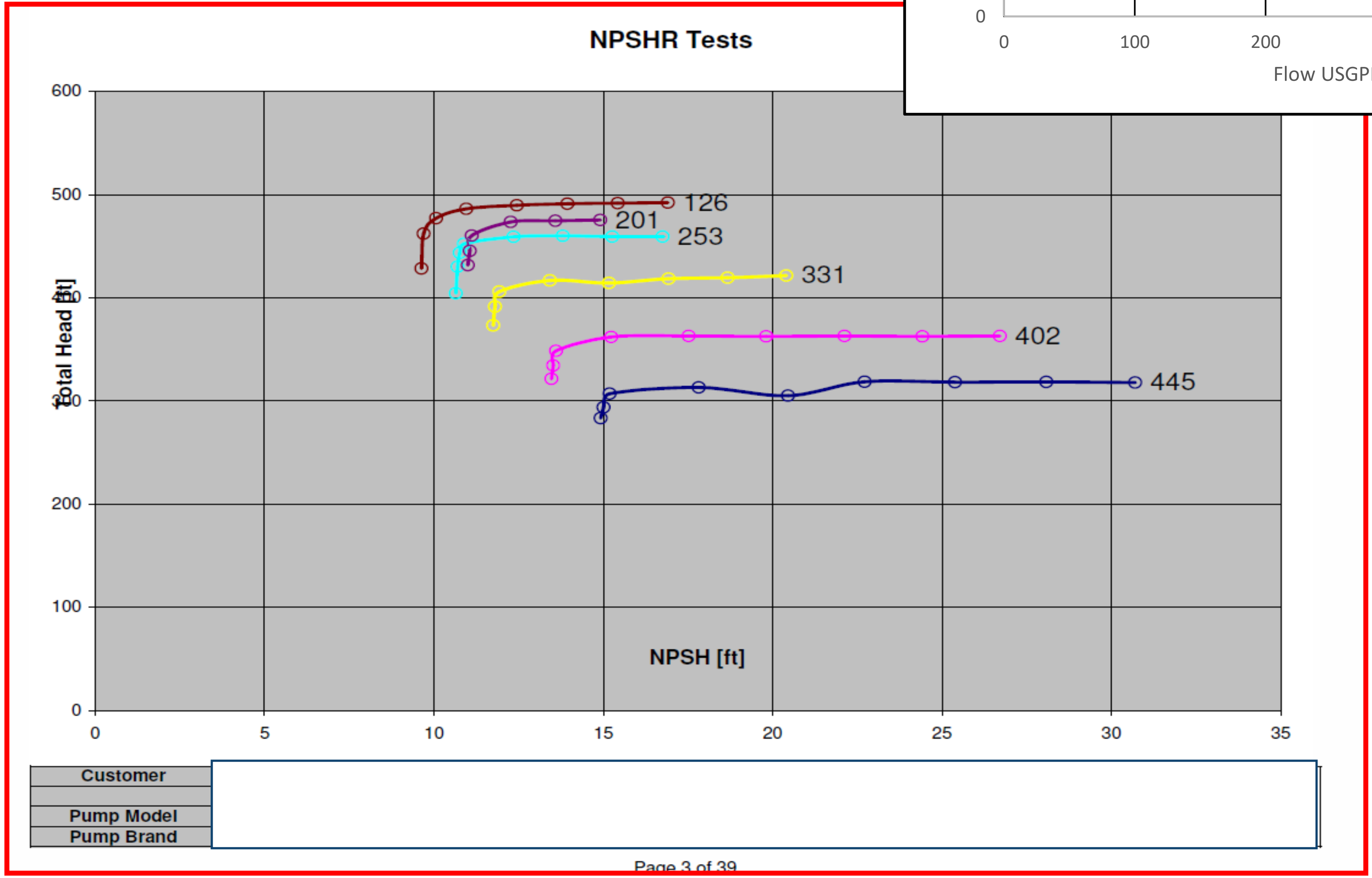
- At each flow point (typically 5 or 6 flows), while the Suction Pressure is reduced, the Discharge Valve is opened slightly to maintain the constant set Flowrate.

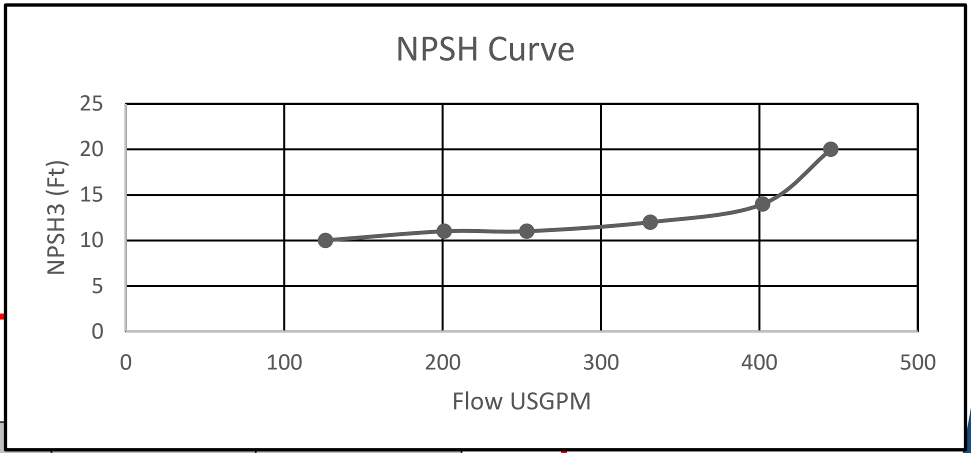
- At each NPSHR Test point, Flow, Head, Suction pressure & Water Temperature readings are taken at progressively lower and lower Suction pressures. Whether the reduction in Suction pressure is due to a Vacuum Suppression Test or a Throttled Suction valve Test.

- At some point, as the Suction Pressure is reduced more and more, the Pump Differential Head will get closer to a 3% Head reduction. So now the Suction Pressure Reduction values are taken closer together.

- After the Head drop has reached 3% at every Flowrate, the NPSH3 test is completed.

NPSH$_R$ NPSH Test Curve





NPSH$_R$

Common Misconception

"Suction cavitation occurs when NPSHa (available) is less than NPSHr (required)."

This is completely wrong and a misunderstanding of the physics involved in a centrifugal pump. Here is why:

• Consider that NPSHr is normally determined where the pump head has already degraded by 3%. By that point there is already extensively developed cavitation in the impeller.

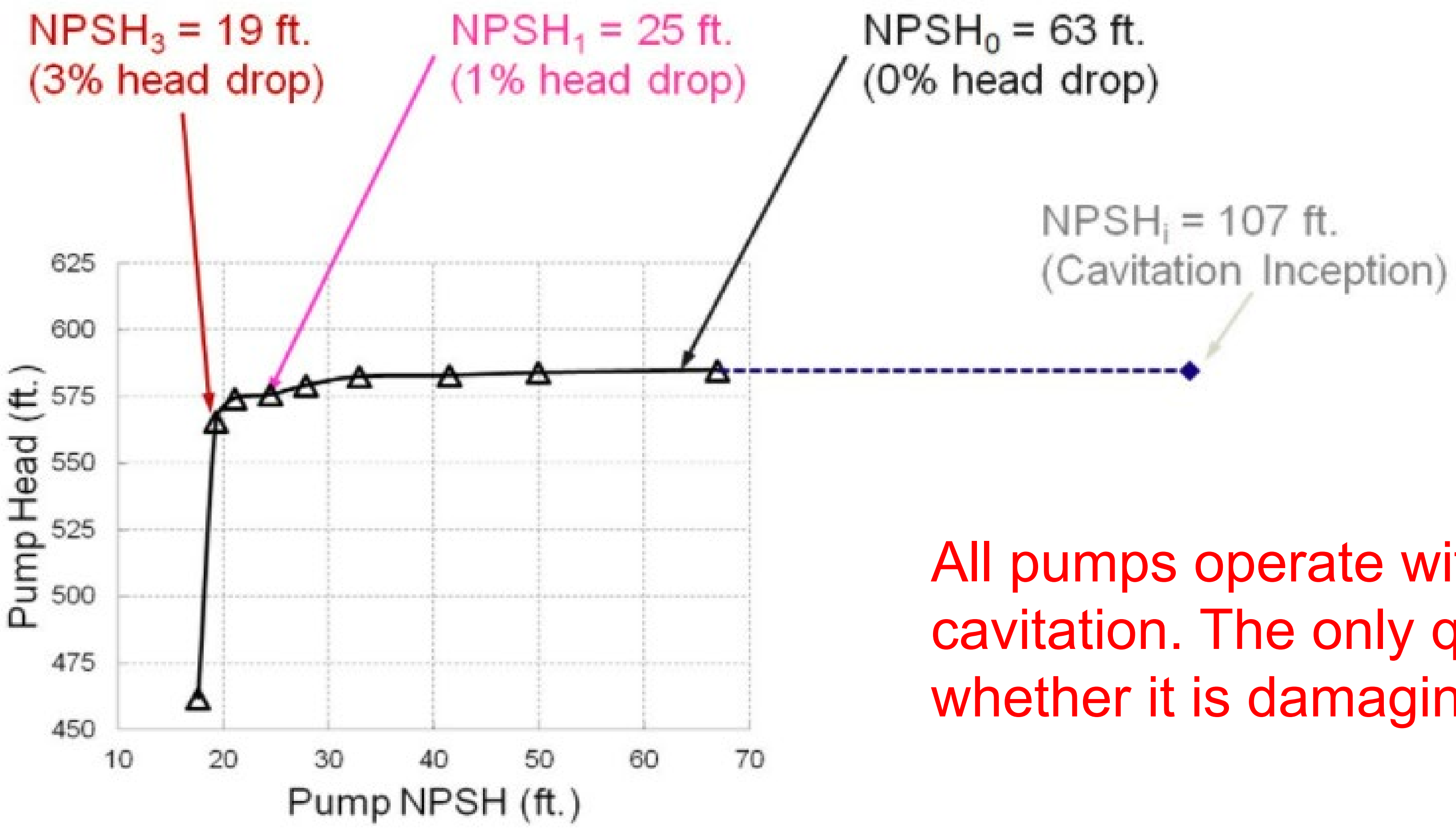
• Simply raising NPSHa slightly above NPSHr does not result in that cavitation magically disappearing. You need to go to much higher suction pressures to completely eliminate cavitation.

• For an "average" centrifugal pump, to **completely** eliminate cavitation, the NPSHa would need to be >500% of the NPSHr (specifically the NPSHi point shown on the example below).

Source – Simon Bradshaw - Director Engineering, Pumps Americas at CIRCOR

$NPSH_R$

Onset of Cavitation



All pumps operate with suction cavitation. The only question is whether it is damaging cavitation.

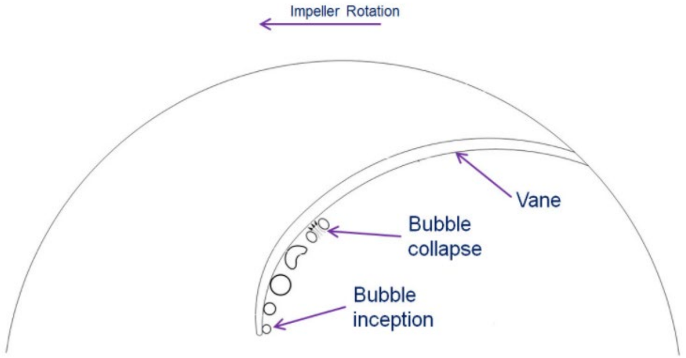
Source – Simon Bradshaw - Director Engineering, Pumps Americas at CIRCOR

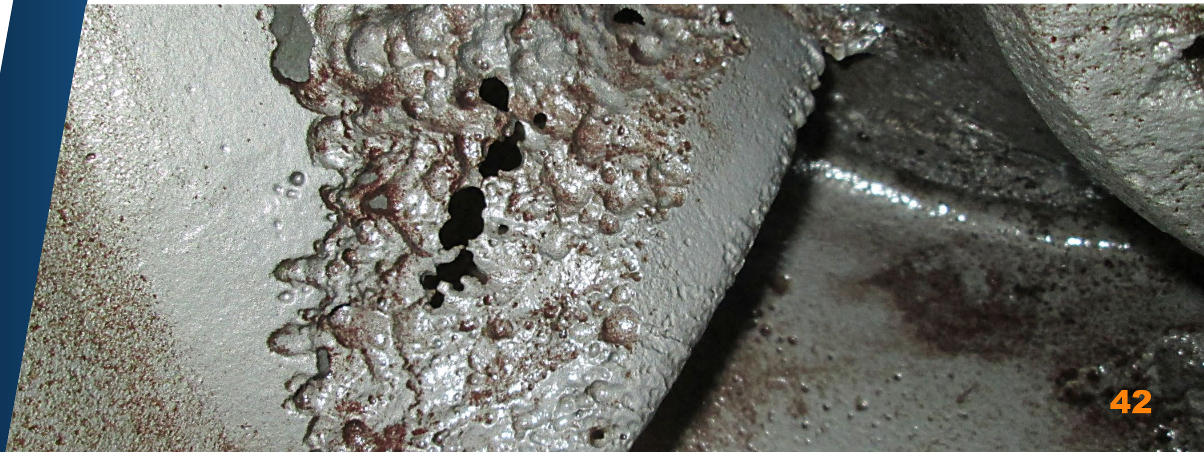
Cavitation

As the suction head value gets closer to the $NPSH_3$ value, vapour bubbles form on the underside of the inlet vanes of the impeller.

The closer you get to the $NPSH_3$ value the more bubbles will form and over a larger area of vane.

As these bubbles are swept into higher pressure areas they collapse with a shock





Cavitation

The Cavitation Mechanism

When a Cavitation vapour bubble collapses, the instantaneous pressure of this small, high energy shock-wave is many thousands of PSI over an extremely small area.

There are two progressive shock waves that impact the metal surface against the bubbles:-

The initial MICRO-JET formed when the top surface of the bubble starts to collapse.

Immediately after this micro-jet, the whole surface of the bubble then collapses & returns to liquid form.

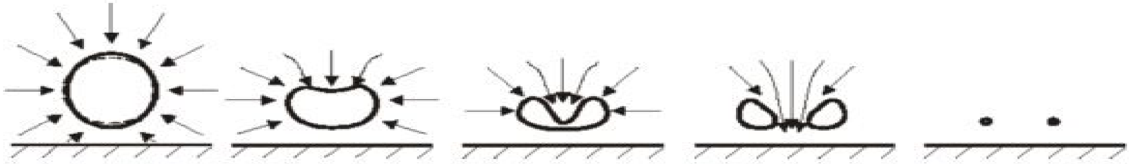
Shock waves are formed by collisions among the surrounding liquid molecules, that rush in to fill the void caused by the collapsing bubble.

Research has shown that the life span of a Cavitation bubble from formation to collapse, is about two milliseconds (two one-thousands of a second), so this event occurs very rapidly.

The more rapidly the surrounding Liquid collides, the greater is the energy of the damaging shock-wave & micro-jet.

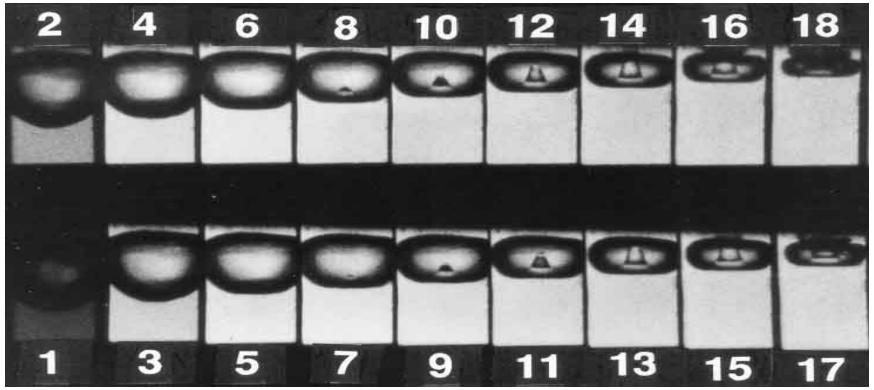
Cavitation

The Cavitation Mechanism

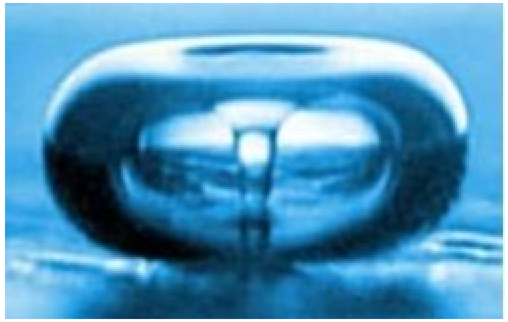


This illustration shows the progression of the vapor bubble collapse.

These ultra-high speed Laboratory photos below show this progression:-



Below is a photo showing the micro-burst jet, just before the final collapse:-



Cavitation

Extent of the Damage

The extent of the damage will depend on several factors:

- The size of the bubbles formed
- The Density of the fluid
- Thermodynamic effects (Enthalpy & Latent heat)

These combined effects comprise “Thermal Cavitation Criteria –B” (see next slide)

But simply put:

- Cold water forms big bubbles and has a high density, so the damage done when the bubbles collapse is high
- Hydrocarbons form small bubbles and have a lower density, so the damage done when the bubbles collapse is much less

Cavitation

Extent of the Damage – in More Detail

COMPARITIVE VALUES OF THE THERMAL CAVITATION CRITERIA-B:-

Below we show a list of the various THERMAL CAVITATION CRITERIA-B values for Water which exhibits high cavitation damage, and Butane, a light hydrocarbon, which usually exhibits a much lower cavitation damage rate.

Thermal Cavitation	**Water**	**Water**	**Water**	**Water**	**Butane**
Criteria B	**70F**	**180F**	**212F**	**300F**	**70F**
Value of B	***253***	***1.048***	***0.324***	***0.0223***	***0.0202***

This shows why one of the worst liquids to produce damaging cavitation erosion is COLD WATER. As this has a very high ratio of vapour to liquid and a high density (relative to hydrocarbons which increases the kinetic energy of the cavitation micro-jet causing the erosion damage.

Cavitation

Hydrocarbon Correction Factor

Allowed by HI

Not allowed by API since 6th edition

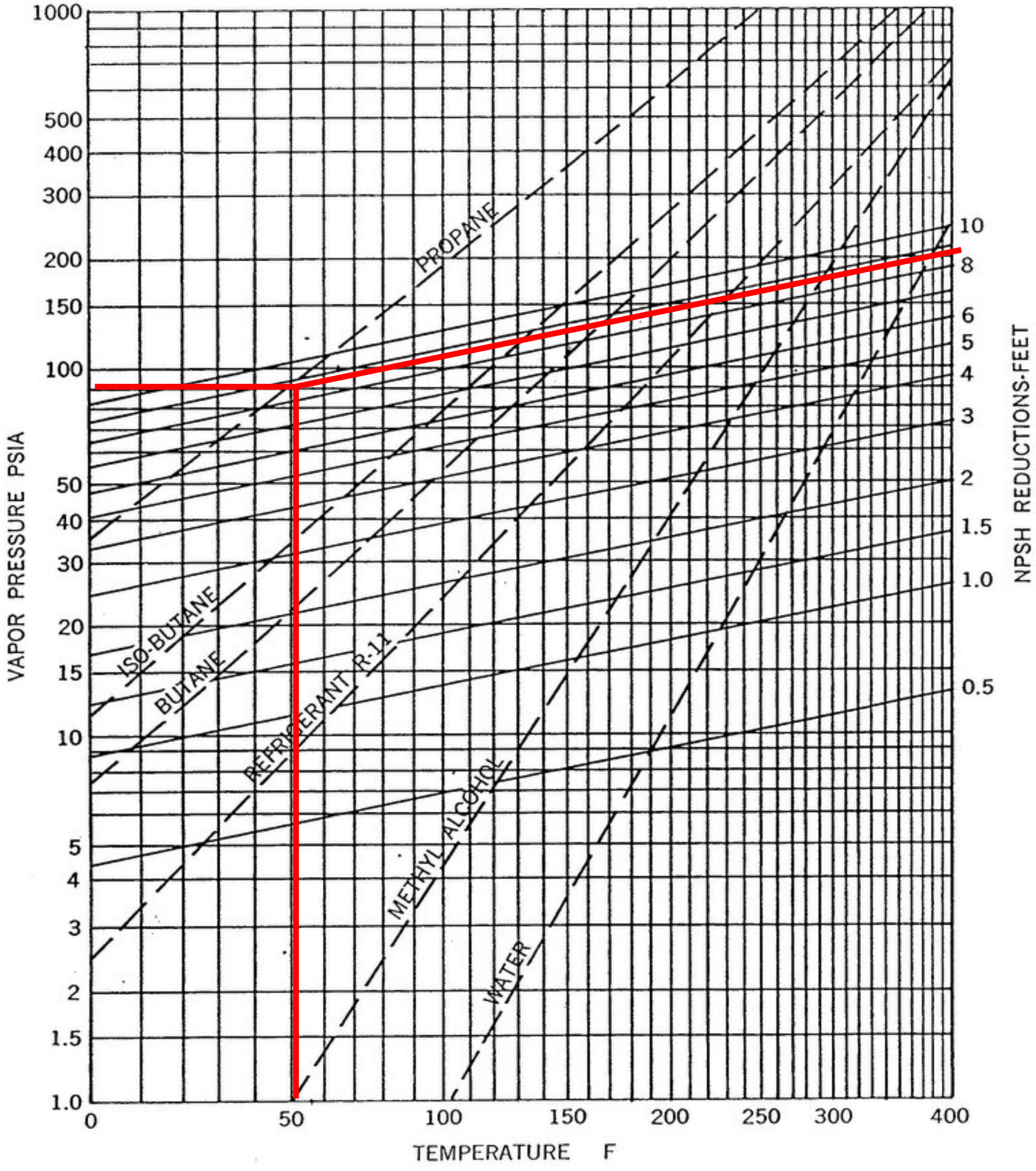


Fig. 61 NPSH REDUCTIONS FOR PUMPS HANDLING HYDROCARBON LIQUIDS AND HIGH TEMPERATURE WATER

Note: This chart has been constructed from test data obtained using the liquids shown. For applicability to other liquids refer to the text.

Cavitation

NPSH Suggested Margins

ANSI / Hydraulic Institute Standard Para 9.6.1 addresses NPSH Margin

API Pumps in hydrocarbon service

NPSH Margin ($NPSH_A$ / $NPSH_3$) = 1.1 or 1m (3.3ft)

in the allowable operating range (AOR)

Chemical Process Pumps

with Nss <11,000, NPSH Margin ($NPSH_A$ / $NPSH_3$) = 1.1 or 0.6m (2ft)

with Nss >11,000, NPSH Margin ($NPSH_A$ / $NPSH_3$) = 1.2 or 1.0m (3.3ft)

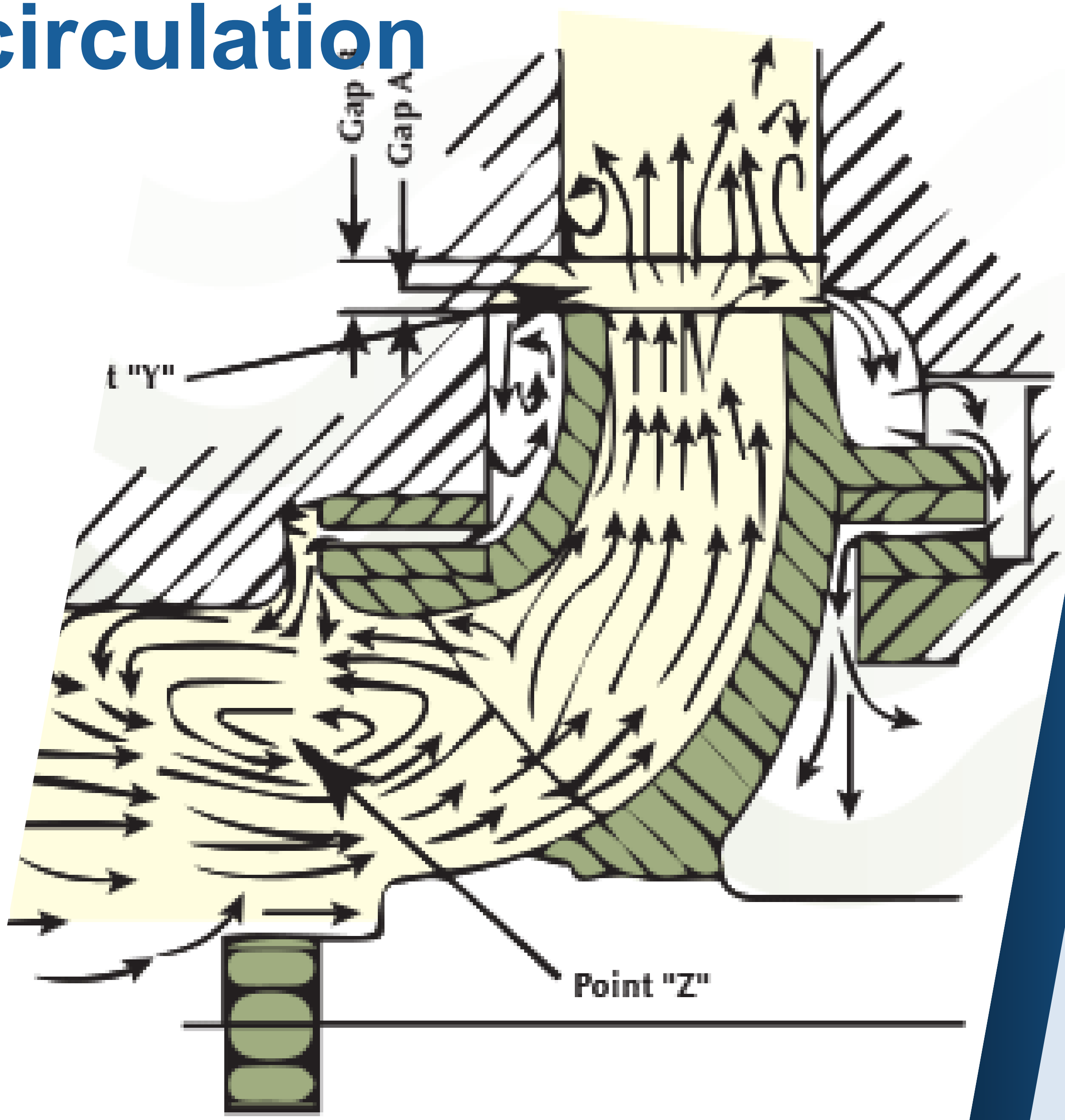
in the allowable operating range (AOR).

Suction & Discharge Recirculation

A Different kind of Cavitation

Occurs when pumps operate back on the curve from BEP

- When two flow paths within a fluid are moving in opposing directions and in close proximity to each other, vortices form.
- These vortices result in low pressure areas (where bubbles form) and high pressure areas (where they collapse).

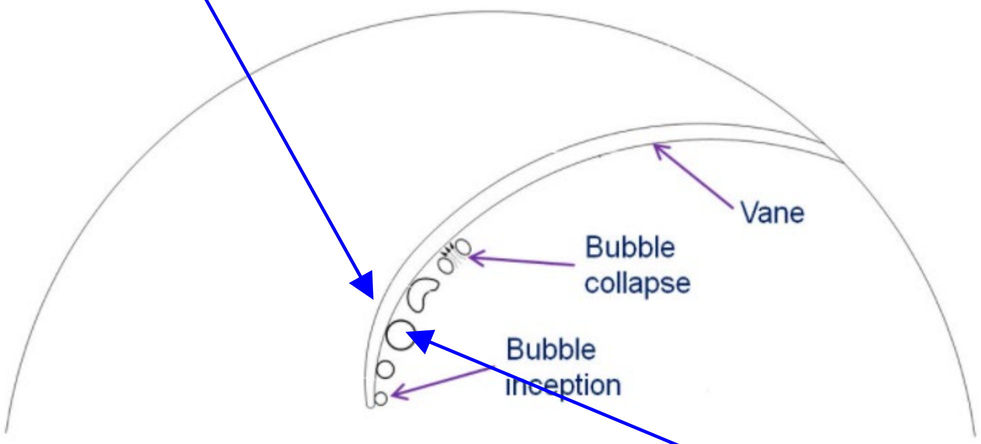


Recirculation vortices at impeller suction eye and at vane tips (sourc
Handbook, Igor J. Karassik and Joseph P. Messina; ISBN-10 007033

Suction Recirculation

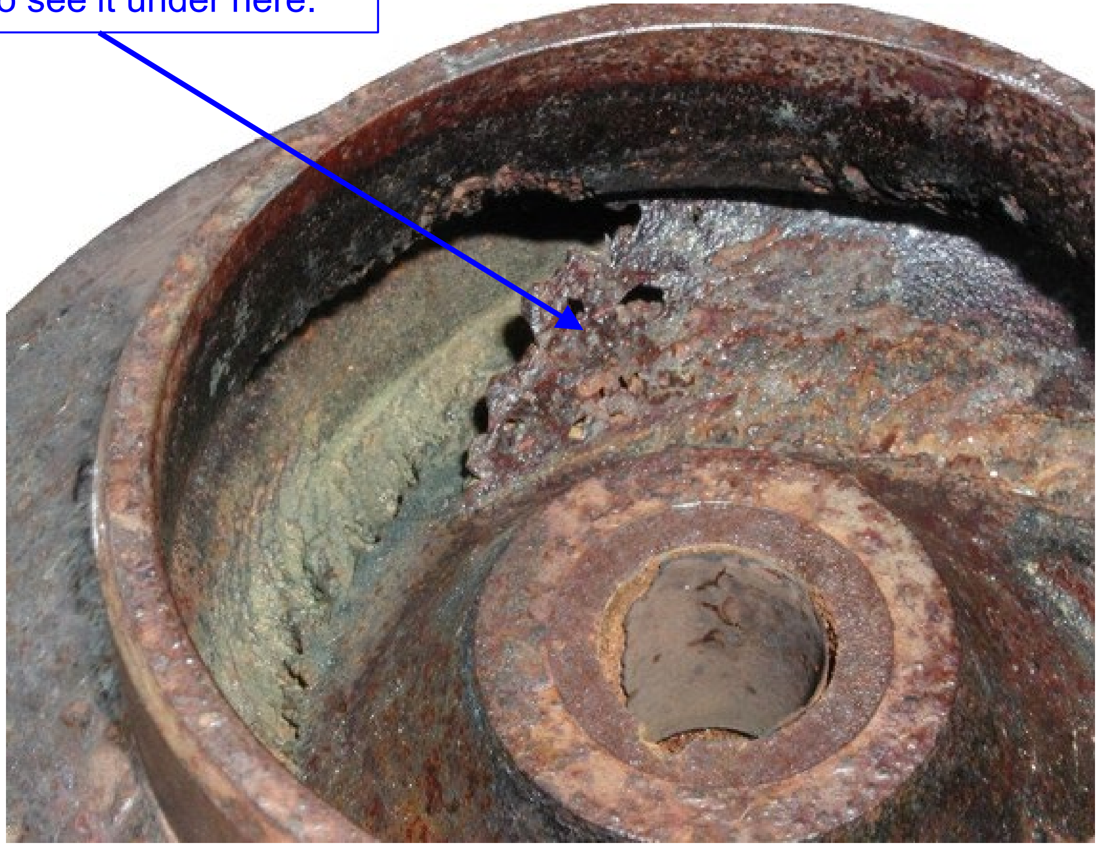
A Different kind of Cavitation

Suction Recirculation Cavitation Damage appears on back side (pressure side) of vane



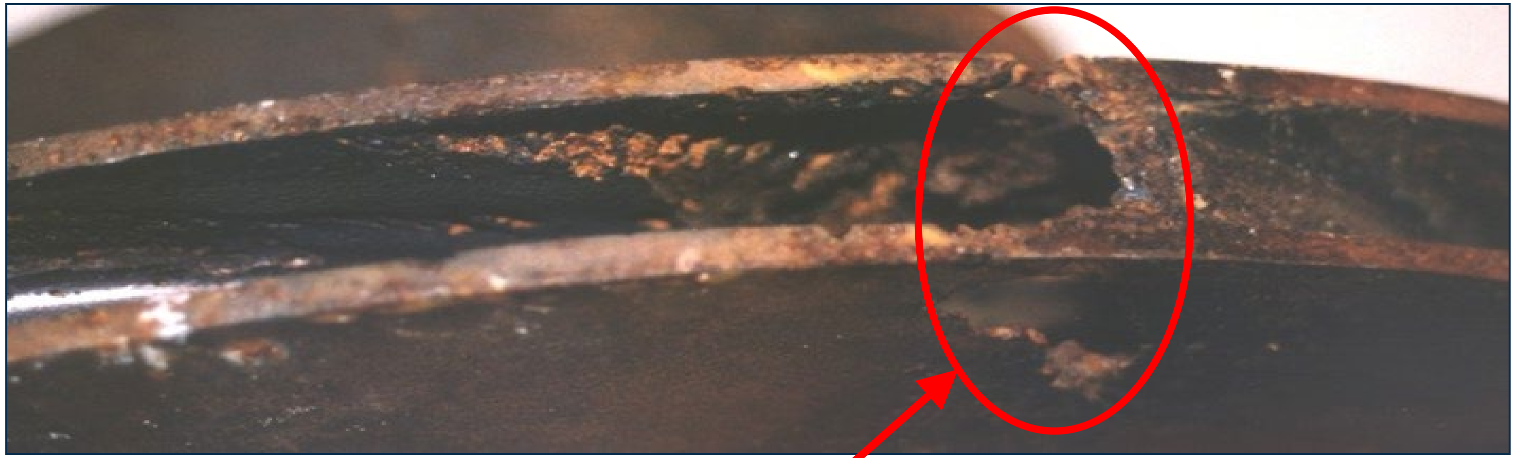
NPSH Cavitation Damage appears on front side (suction side) of vane

Suction Recirculation Cavitation Damage appears on back side (pressure side) of vane. You need a dentist's mirror to see it under here.



Discharge Recirculation

A Different kind of Cavitation



The central core of the Discharge Recirculation Vortex, is such a low pressure that the liquid starts to vapourise & as the bubbles move to the outer area of the vortex, where the pressure is much higher, they Cavitate (implode) against the Impeller Shrouds, and cause the hole damage shown.

Cavitation – Which Type Have I Got?

The quickest and easiest way to identify the real cause of the noise, loss of performance, reduced power & vibration, is merely to throttle the discharge valve…

This will cause the pump flow to reduce, so that one of three events will occur, which allows the true cause to be found:-

Event 1:- If the rumbling & rattling sound reduces, or in fact may be eliminated entirely….

The pump is now running at a lower flow with lower NPSHR requirements. ***So this event indicates that NPSH Cavitation was the real culprit.***

Event 2:- If the rumbling & rattling sound, and the vibration increases…..

This tells us that the pump is moving into a lower flow condition causing the situation to get worse. ***So this event indicates that Suction and/or Discharge recirculation was the real culprit.***

Event 3:- OR- If the result, is that there is no change in the sound or vibration……

This tells us the events are unaffected by flow. ***So this event indicates that Air or Gas entrainment in the Liquid was the real culprit.***

Cavitation Damage

How can I Minimise or Mitigate the Damage?

THE FOLLOWING MATERIALS ARE PROGRESSIVELY MORE RESISTANT TO EROSION & CAVITATION DAMAGE. STARTING WITH CAST IRON AS THE LEAST RESISTANT:-

1. Cast Iron…………… Least Resistant.
2. Leaded Bronze.
3. Cast Carbon Steel.
4. Manganese Bronze.
5. Monel.
6. Chrome and Stainless Steels:-
   CA15 & CA6NM (Martensitic) & CF8M (Austenitic).
7. Cast Duplex Stainless Steels.
8. Cast Nickel Aluminum Bronze.
9. Alloyed Titanium.
10. Cast Carburized 12% Chromium Stainless and Chrome Manganese Austenitic Steels....................Very Resistant.
11. Stellite coating……………….Most Resistant.

Coming Attractions ☺

"Overhung Process Pumps"

Thurs 3rd November – 08.00 (UK GMT) (Eastern Hemisphere) &

17.00 (UK GMT) (Western Hemisphere)

Comparing and contrasting OH1 and OH2 pumps primarily, but also discussing vertical overhung pumps (OH3,4,5 & 6)