Hydraulic Considerations in Pumping System Design

VWEA Wastewater Operations Education Conference
Roanoke Virginia
July 14, 2016

Agenda

- Basics of Hydraulics and Pump Operation
- Pumping System Design Process
  - Types of Pumps
  - System Curve Development
  - Pump Station Layout
  - Pump Selection Considerations
  - Hydraulic Concerns
- Case Studies
- Summary
- Questions

Abbreviations and Acronyms

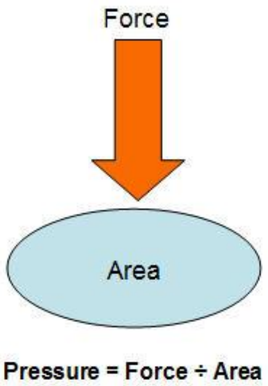
- BEP – best efficiency point
- BHP – brake horsepower
- fps or ft/sec – feet per second (velocity)
- FM – force main
- gpm – gallons per minute (flow)
- H – Head (feet)
- HP – horsepower
- n – rotational speed
- $NPSH_A$ – net positive suction head available
- $NPSH_R$ – net positive suction head required
- psi – pounds per square inch (pressure)
- Q – Flow Rate (gpm, mgd, cfs…)
- rpm – revolutions per minute
- TDH – total dynamic head

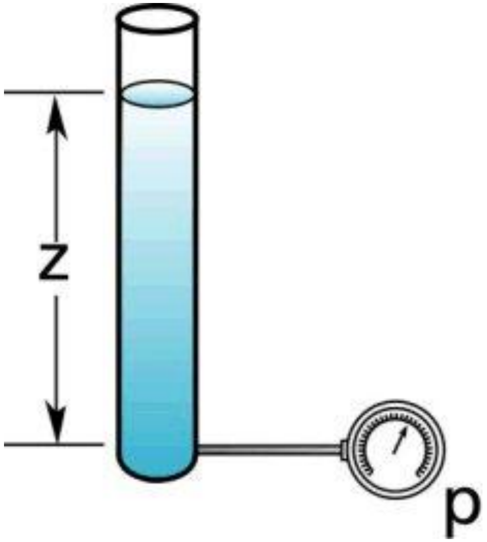
Basics of Pump Operation

- A pump lifts fluid from one elevation to another
- Work is needed to lift fluid
- Work is independent of type
  - Human Power
  - Animal Power
  - Wind Power
  - Steam Power
  - Electrical Power
- Pump can lift continuously or in increments
- Take-away:
  - Higher lift requires more work
  - Higher flow requires more work
  - Faster work requires more power

Pressure Head (Head)

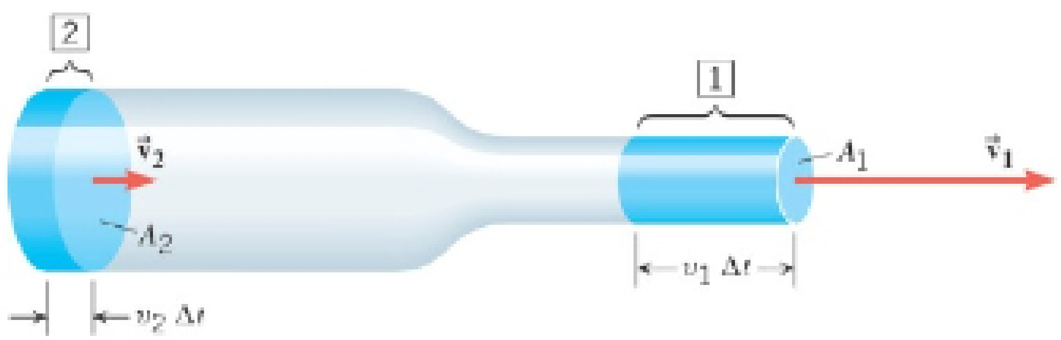
- Pumps deliver fluid against pressure
- Pressure = Force / Area (psi)
- Head (feet) is commonly used to express pump operating pressure
- A 2.31 foot high column of water exerts a pressure equal to 1 psi
- i.e. Car tires ~ 35 psi = 81 feet of head





Closed Conduit Flow (Q)

- Volume of fluid passing per time (gpm, mgd, cfs…)
- Q (cfs) = Area (ft^2) x Velocity (fps)
- For a given flow, the smaller the conduit the larger the velocity.
- Higher velocity translates into increased frictional headloss



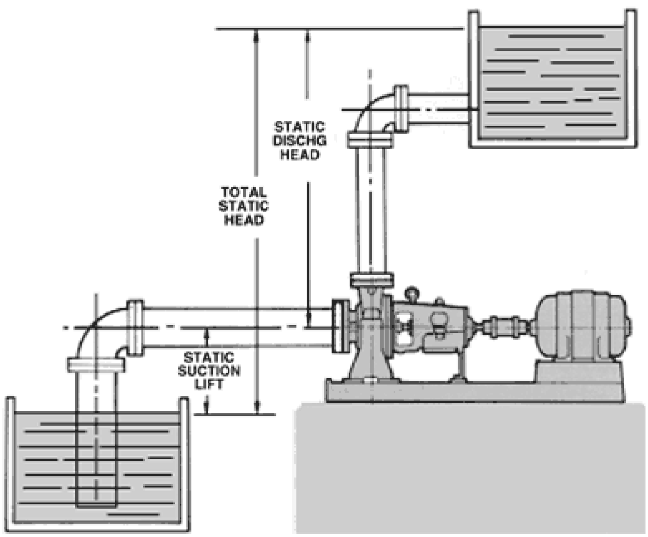
Total Dynamic Head (TDH)

- TDH is the total amount of head a pump must operate against to deliver wastewater to a desired location
- TDH = Static Head + Head Loss (HL)
- Static Head – exists when pump is on or off
- Head Loss – exists only when fluid is pumped

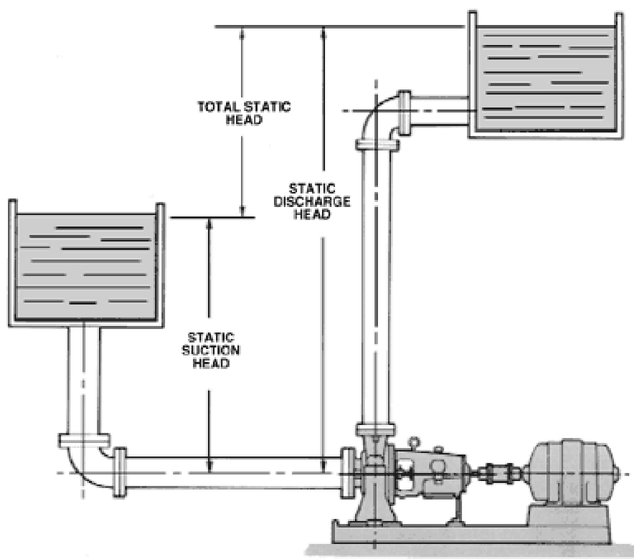
Static Head

For free surfaces:

- Static Head = Discharge Tank WSEL – Suction Tank WSEL
- Static Discharge Head = Discharge Tank WSEL – Pump CL
- Static Suction Head = Suction Tank WSEL – Pump CL



Suction Lift – Negative Suction Head



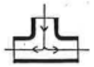
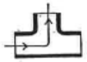
Flooded Suction – Positive Suction Head

Dynamic Head (Head Loss)

- Energy dissipated due to friction and turbulence during pump operation

- Major Losses (Friction Losses)
  - Due to friction between pumped water and inner surface of piping
  - $H_f = 3.02\ L\ D^{-1.167}\ (V/C_h)^{1.85}$ (Hazen-Williams Formula) where:
    - L is length of pipe (feet)
    - D is diameter of pipe (square feet)
    - V is mean velocity (fps)
    - C_h is Hazen-Williams friction coefficient (new up to 140 and old as low as 80)

- Minor Losses
  - Due to turbulence at bends, fittings, valves, etc.
  - $H_f = K\ (V^2/2G)$ (Headloss factor times velocity head)

Nature of Special Resistance	Loss in Terms Multiple of $V^2/2g$
Reducers (Vel. of small end)	
Ordinary	0.25
Bellmouthed	0.10
Standard	0.04
Bushing or coupling	0.05 - 2.0
Tee	
Standard 	1.50
Ditto	1.80
Standard (through side outlet) 	1.80
Standard (run of Tee) 	.60
Run of Tee Reduced 1/2	.90
Run of Tee Reduced 1/4	.75
90° Bend	
Short radius elbow (screwed fittings)	.9
Medium radius elbow (screwed fitting)	.75
Long Radius elbow (screwed) (See p. la for flanged fittings) (See also values for Losses in Conduits)	.60
Square Elbow (See also p. la)	
Intersection of two cylinders, corners not rounded at outside nor inside. e.g. welded pipe	1.25
Ditto	1.8
Return Bend (screwed) See also p. la	2.2
45° Bend (See also p. la)	.42
Also General rule to use 3/4 of loss for 90° bend of same radius.	
Standard 45° Bend (4-18")	0.20 - 0.30

Net Positive Suction Head (NPSH)

- $NPSH_A$ = Atmos. Head + Static Suction Head – Suction HL
  - Standard atmospheric pressure = 14.7 psi (34 ft. head)

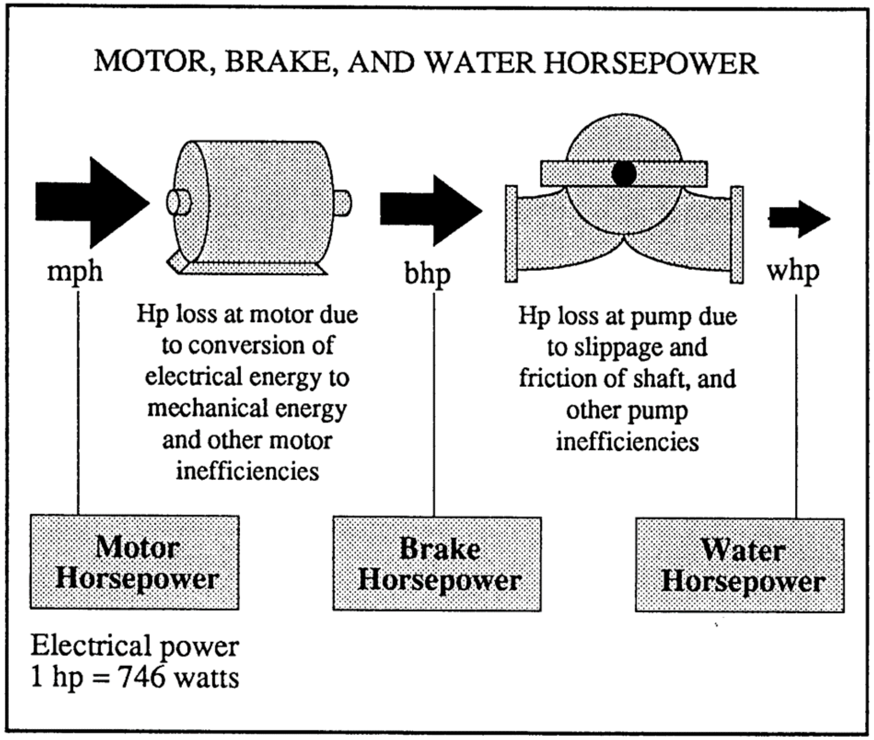
- Net Positive Suction Head Required ($NPSH_R$)
  - Furnished by pump manufacturer – pump specific
  - Increases with pump flow

- $NPSH_A < NPSH_R$ → Cavitation
  - Typically occurs in systems with static lift
  - Could occur in flooded suction scenario with extremely long lengths of suction piping

- Insufficient submergence can lead to vortexing

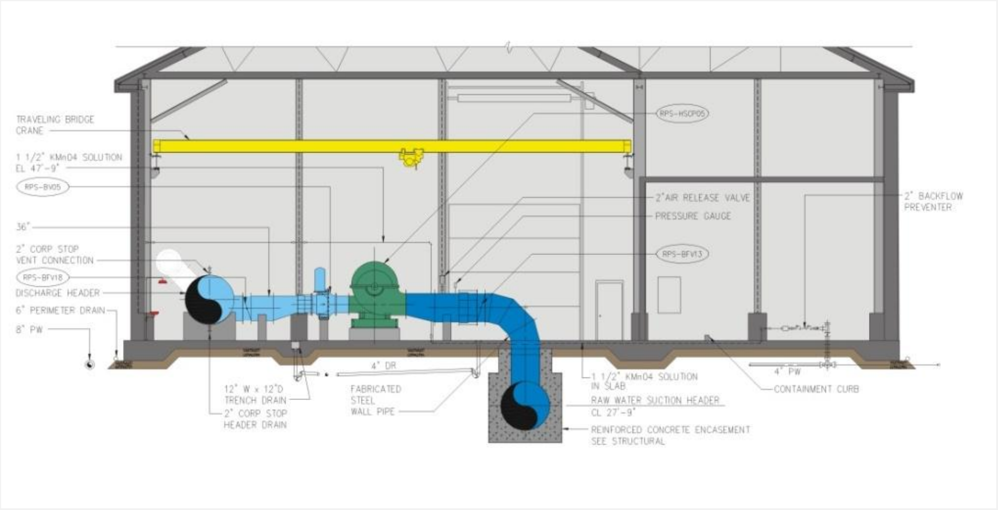
Work & Power

- Work
  - A force does work when it acts on a body over a distance
  - Units of foot pound (ft-lb)
  - Wastewater pumps do work to move the wastewater
- Power
  - Rate of work done (ft-lb/s)
  - Wastewater pumps most often do work by using electric motors
  - Motors are commonly rated by horsepower (hp)
  - 1 unit of hp is equal to 550 ft-lbs/s



The Pumping System Design Process

- Collect information
- Determine type of pump to be used
- Develop station layout
- Develop system curves
- Select pumps that match the system curves
- Write your specification
- Coordinate
- Finalize the design



Collect Information

- What – type of fluid is to be pumped?
  - Fluid properties: density, viscosity, solids content, temperature
- From where to where?
  - System characteristics: friction and minor losses, suction lift, static head, other pumps operating simultaneously
- How much – what are design flowrates?

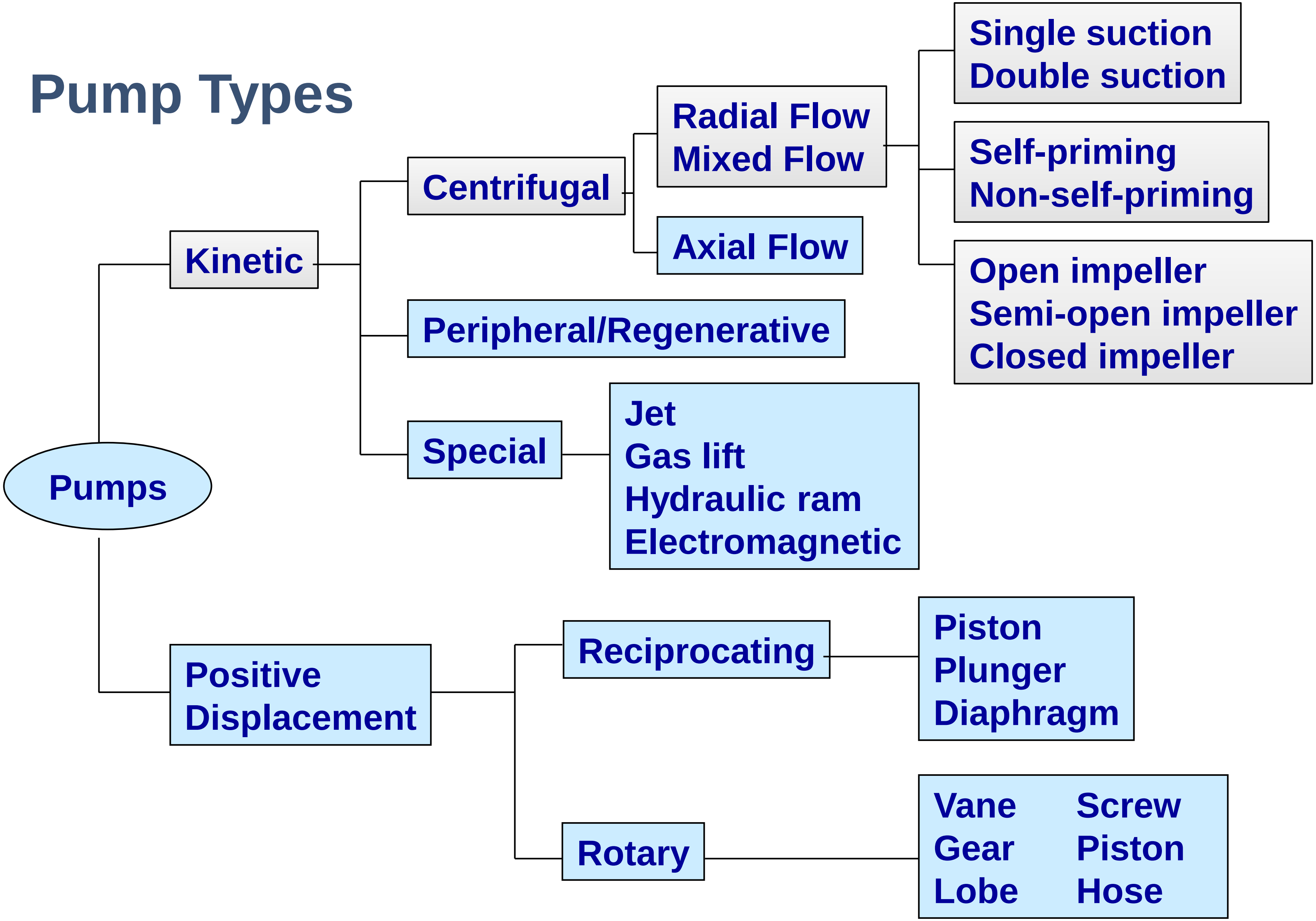
Determine Type of Pump

- Flow and head requirements
- Type of fluid, solids content
- Site conditions
  - Footprint and headroom constraints
  - Subgrade conditions
  - Elevation constraints
    - Suction and discharge inverts
    - Suction head available

More than one type may work - what's best for the specific application and owner preference?

Fairbanks-Morse

Pump Types


Pumps
Kinetic
Centrifugal
Radial Flow
Mixed Flow
Axial Flow
Single suction
Double suction
Self-priming
Non-self-priming
Open impeller
Semi-open impeller
Closed impeller
Peripheral/Regenerative
Special
Jet
Gas lift
Hydraulic ram
Electromagnetic
Positive Displacement
Reciprocating
Piston
Plunger
Diaphragm
Rotary
Vane
Gear
Lobe
Screw
Piston
Hose

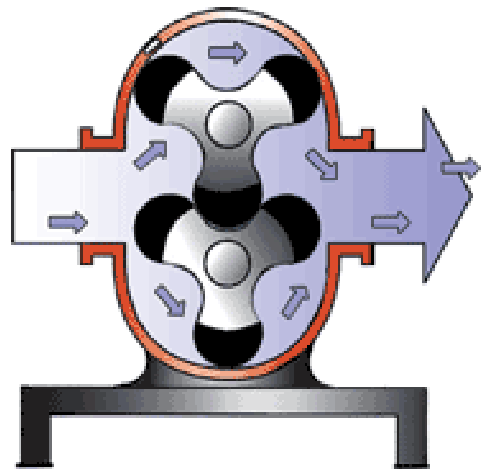
Types of Pumps

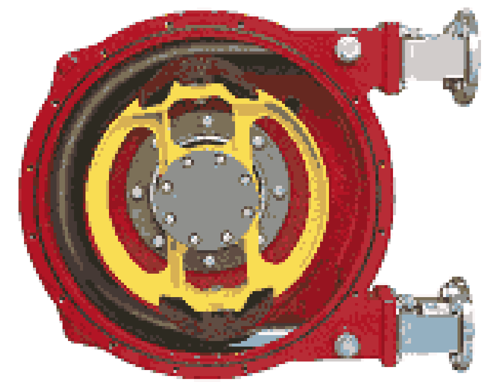
- Kinetic (Rotodynamic) Pumps
  - Energy is imparted to the fluid by a rotating impeller which increases the flow velocity and converts to a pressure increase upon exit.
  - Can be safely operated under closed valve conditions (for short periods of time).
  - Three Types:
    - Radial-flow pumps (Centrifugal Pump) - higher pressures and lower flow rates than axial-flow pumps.
    - Axial-flow pumps - lower pressures and higher flow rates than radial-flow pumps.
    - Mixed-flow pumps – A compromise between radial and axial-flow pumps - operate at higher pressures than axial-flow pumps while delivering higher discharges than radial-flow pumps.

- Positive Displacement (PD) Pumps
  - PD pumps physically displace fluid
  - Closing a valve downstream can lead to continual pressure build up and failure of pipeline

Positive Displacement Pumps

HP Reciprocating Triplex Pump

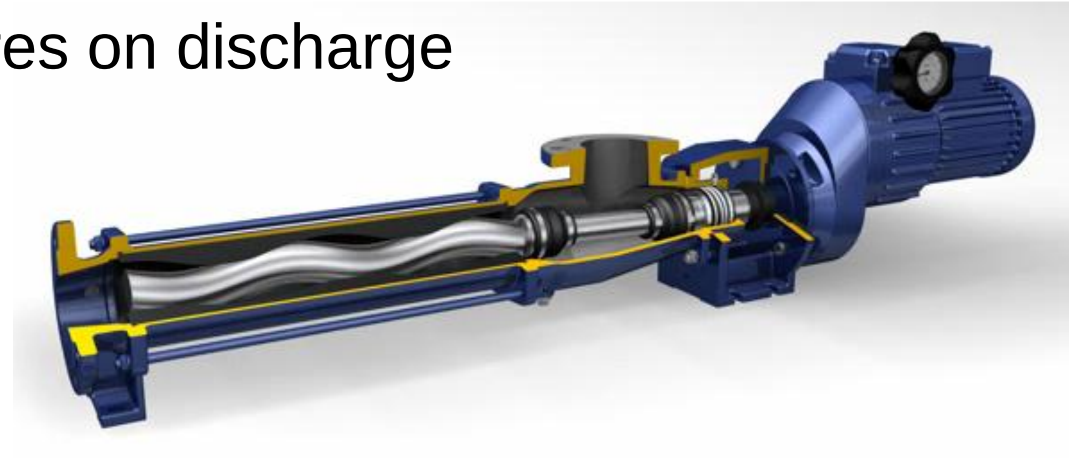




Progressing Cavity Pump

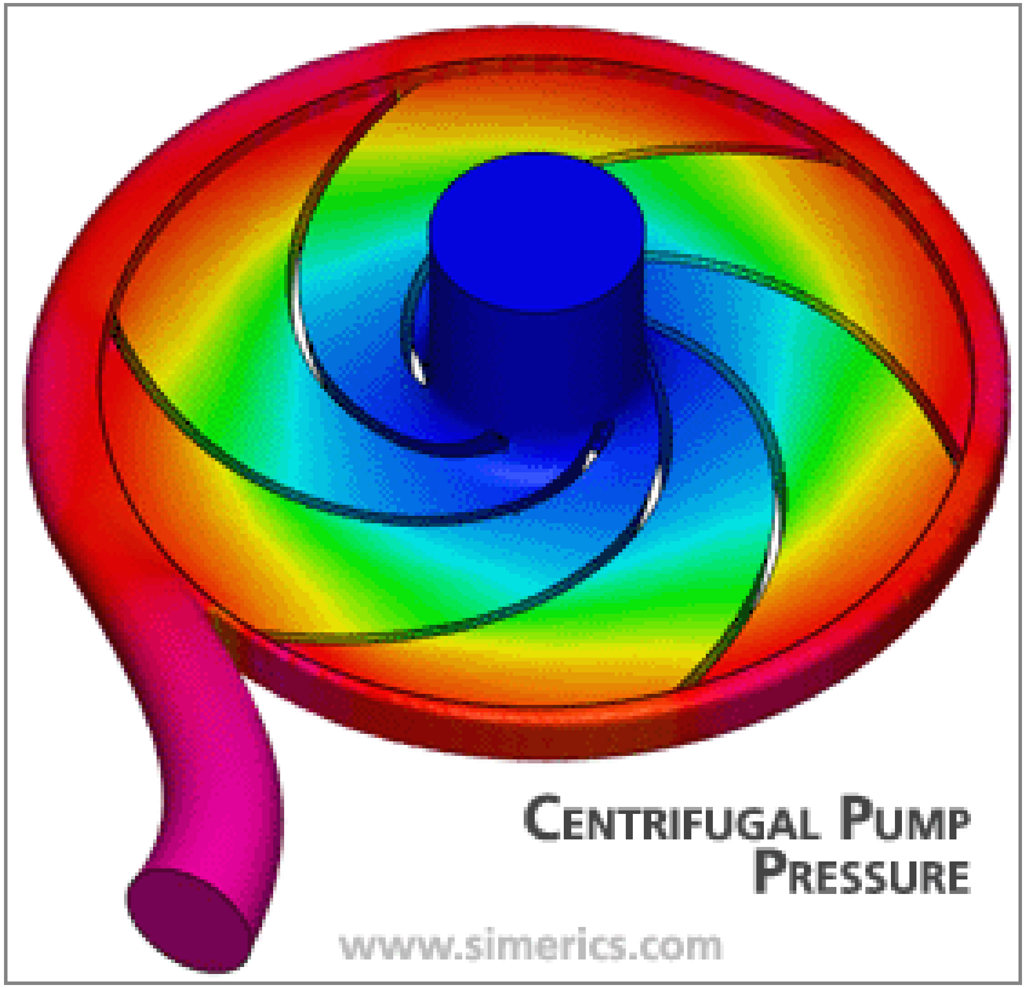
Progressing Cavity Pumps

- Flowrate fixed to speed
- Capable of pumping highly viscous stream
- Commonly used in sludge and slurry pumping applications
- Operates at high pressures
- Must avoid running pump dry
- Provide safety features on discharge



Centrifugal Pump

A centrifugal pump lifts fluid from one elevation to another by continuously adding kinetic energy (accelerating the fluid) using a rotating impeller



Common Types of Centrifugal Pumps for Water and Wastewater

- Horizontal Split Case Pumps
- Vertical Turbine Pumps
- End Suction Pumps
  - Closed impeller
  - Non-Clog pumps
  - Submersible non-clog pumps

Horizontal Split Case

Applications

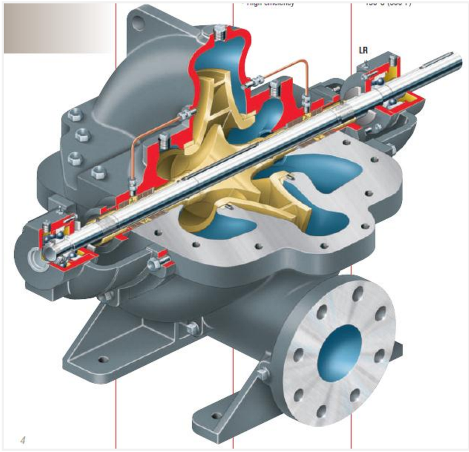
- Water treatment:
    - Raw Water
    - High service pumping
    - Transfer pumping
- Wastewater treatment:
    - Reuse filter feed
    - Reuse distribution
    - Treated effluent pumps

Configurations

- Horizontal motor
- Vertical motor
- Single or two stage
- Dual diesel / electric drive

Characteristics

- Wide flow range
- Heads to ~500 ft. for single stage, higher for two-stage
- High efficiency (85-95%)
- Ease of maintenance
- Flat curve



Horizontal

Vertical

Vertical Turbine

Applications

- Water treatment:
  - Raw water pumps
  - Groundwater pumps (submersible)
  - Membrane feed pump
  - Filter backwash pump
  - High service pumps
  - Transfer pumps

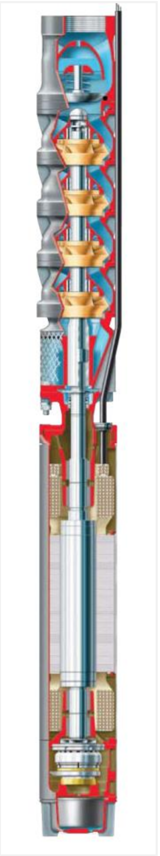
- Wastewater treatment:
  - Reuse filter feed
  - Reuse distribution pumps
  - Treated effluent pumps
  - VTSH (vertical turbine solids-handling)

Characteristics

- Wide flow range
- Wide head range – add stages for higher head
- Steep curve
- Very compact footprint
- Prone to vibration
- Difficult to service

Configurations

- Can-type
- Wetwell-mounted
- Submersible



End Suction

Applications

- Water treatment:
  - Booster Pumping
  - Filter Backwash
  - Membrane Feed
  - Chemical Feed
  - Raw water
- Wastewater treatment (non-clog impellers):
  - Sewage lift stations
  - Raw sewage pumps

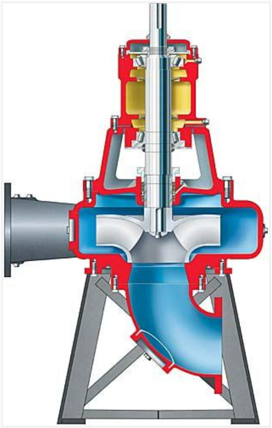
Characteristics

- Low to Medium flow
- High head - add stages
- Curve shape varies

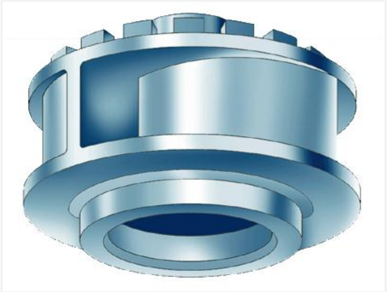
Configurations

- Vertical - save space or to mount motor above flood elevation
- Horizontal - provides good access and saves head room
- Close-coupled (single pump/motor shaft)
- Direct coupled (motor shaft connected to the pump shaft by a shaft coupling)
- V-belt drive
- Extended shaft
- Submersible

End Suction Pumps – Wastewater



- Heads to ~250 ft. for a single stage
- Best efficiencies 70-75%
- Impeller options:



Channel Impeller

(enclosed, 1-3 vanes)

Semi-Open Impeller

Vortex Impeller

(recessed impeller)

Sewage lift station typical application

Grit and sludge pumping typical applications

Solids handling performance improves →

← **Hydraulic efficiency increases**

Pump Type Selection Example – Griffith RWPS

Selected horizontal split-case pumps – why?

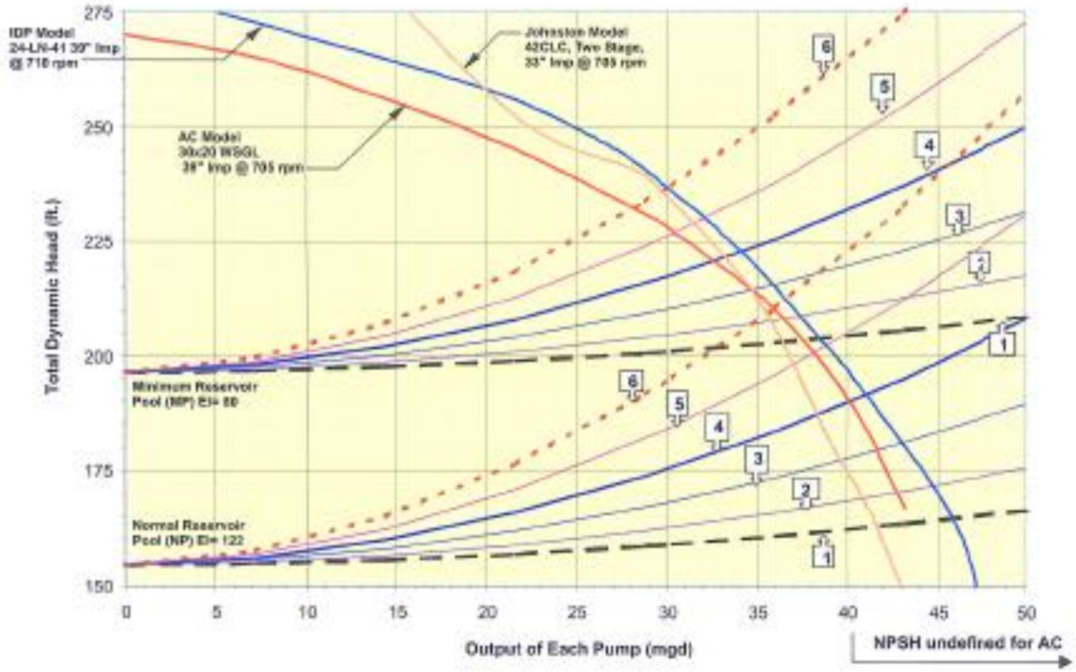
- Had available land area and suction head

- Rock subgrade

- Suitable curve shape

- Owner preference

- Ease of maintenance



Centrifugal Pump Summary

- Larger impellers - Greater flow and head
- Greater Speed – Greater flow and head
- Larger, slower impellers are more efficient but cost more
- Pumps in parallel - more flow at same head
- Pumps in series - higher head at same flow
- Generally, power increases as flow increases to run out
- Best efficiency point (BEP) is at max of efficiency curve

Centrifugal Pumps - Points to Watch

- Rotational speeds ≤ 1,800 rpm
  - Non-clog in particular
- Flooded suction - no priming needed
- Curve shall continually rise to shut off
- Steeper pump curves are best for VFDs
- Duty point to be ~75% Q_{max}, close to BEP
- Aim for efficiencies > 75% single stage
- Size motor HP for “run out” or maximum power NOT duty point

Station Layout - Where to Start?

- Resources
  - Hydraulic Institute (HI) Standards, other references
- Consider constraints – site, budget, etc.
- Collect/develop information needed to create system curves
  - Elevations of suction, pump room floor, high points, discharge
- For retrofits, survey/measure existing elevations, test existing pumps for flow and pressure
  - Develop piping system layout, list of minor losses

Station Layout Considerations

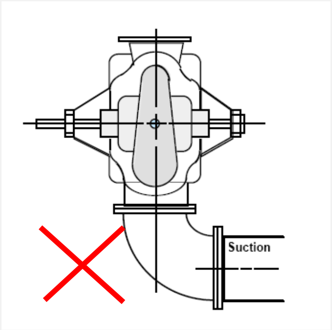
- Provide sufficient work space between pumps
- Use largest pump and motor dimensions (now or future)
- Allow for expansion
- Think through process of installing/removing pumps and valves
  - Size crane and openings for heaviest / largest single item in the station
  - Ensure crane can reach everything it needs to lift
  - Consider need for portable hoists or truck access, etc. when selecting pump spacing, sizing hallways
- Involve operations and maintenance staff early

Layout - Hydraulic Institute Standards

- American National Design Standards for Pump Intake and Centrifugal Pumps
- Wetwells - different designs for clear and solids-bearing liquids
  - Provide steady, uniform flow with minimal flow disturbances
  - Keep solids entrained
- Piped intakes – recommended piping configurations, velocity limits
- Canned vertical turbine pumps – geometry and velocity specifications
- No flow disturbing fittings within 5 pipe diameters of suction
  - Long-radius bends and full-port valves are not considered flow disturbing

Hydraulic Institute
Creating Pump Standards Since 1917

Points to Watch – Suction and Discharge Piping

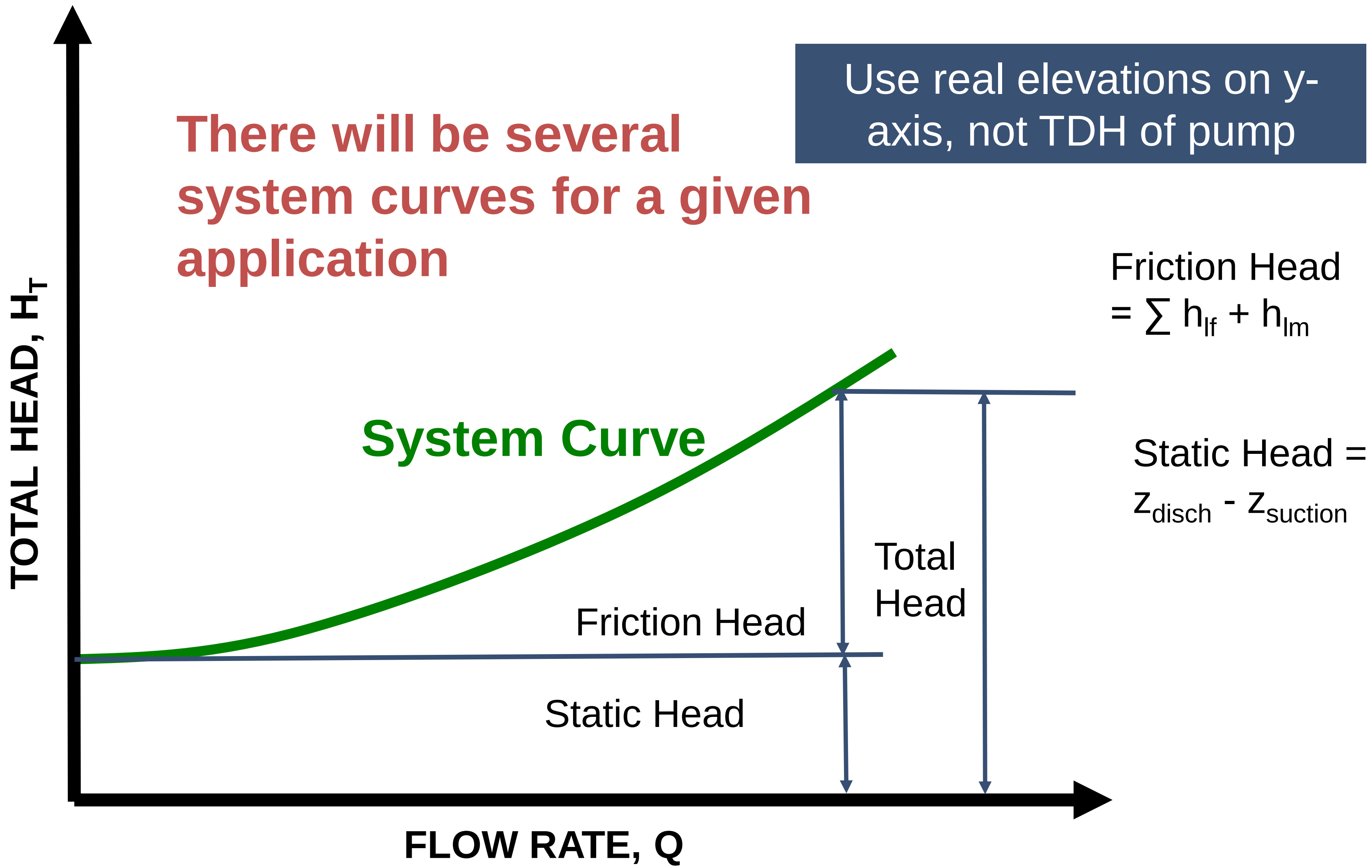


- Suction pipe velocities ≤ 6 ft/s
- Delivery pipe velocities ≤ 8 ft/s
- Avoid applying forces (especially unbalanced ones) to pumps via piping and valves
  - Provide pipe supports
  - No horizontal bends near pumps
- Use long radius elbows for vertical suction bends

- Avoid creating high points
  - On suction, use eccentric reducers with flat side up
  - Continuously rising discharge pipe alignment
- Provide isolation valves
- Include restrained flexible couplings
- Pipe/flanges rated for worst case pressures, including surge / test pressures

Developing System Curve

Use real elevations on y-axis, not TDH of pump



System Curve Worksheet

Example Pump Station

Force Main Conditions:		Hazen-Williams C:	120
Flow Scenario:	ADF(mgd)	0.875 Peak (mgd)	2.5

Number of Pumps=	1				
Total Static Head=	102.42		Coefficients for Flow Units=		
Flow Unit=	GPM		CFS	GPM	MGD
Fric=	10.557		851527	10.557	1908780
Form=	0.002594		522.55	0.0025936	1250.6

DEFINE PIPE SYSTEM

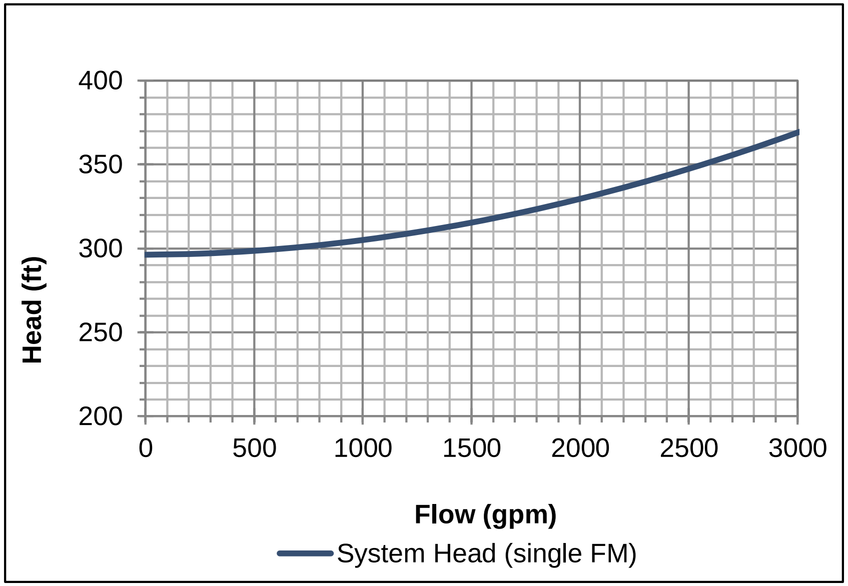
Pipe Reach	Dia. (in.)	Length (feet)	H&W C	Frac Q	Sum K	Kf	Km
A	10	11	120	1	1.27	2.231E-07	3.294E-07
B	8	12	120	1	5.54	7.214E-07	3.508E-06
C	16	9	120	1	2.24	0.000E+00	0.000E+00
D	14	2949	120	1	6.85	1.162E-05	4.625E-07
E	14	2625	120	1	2.2	1.034E-05	1.485E-07

SYSTEM CURVE

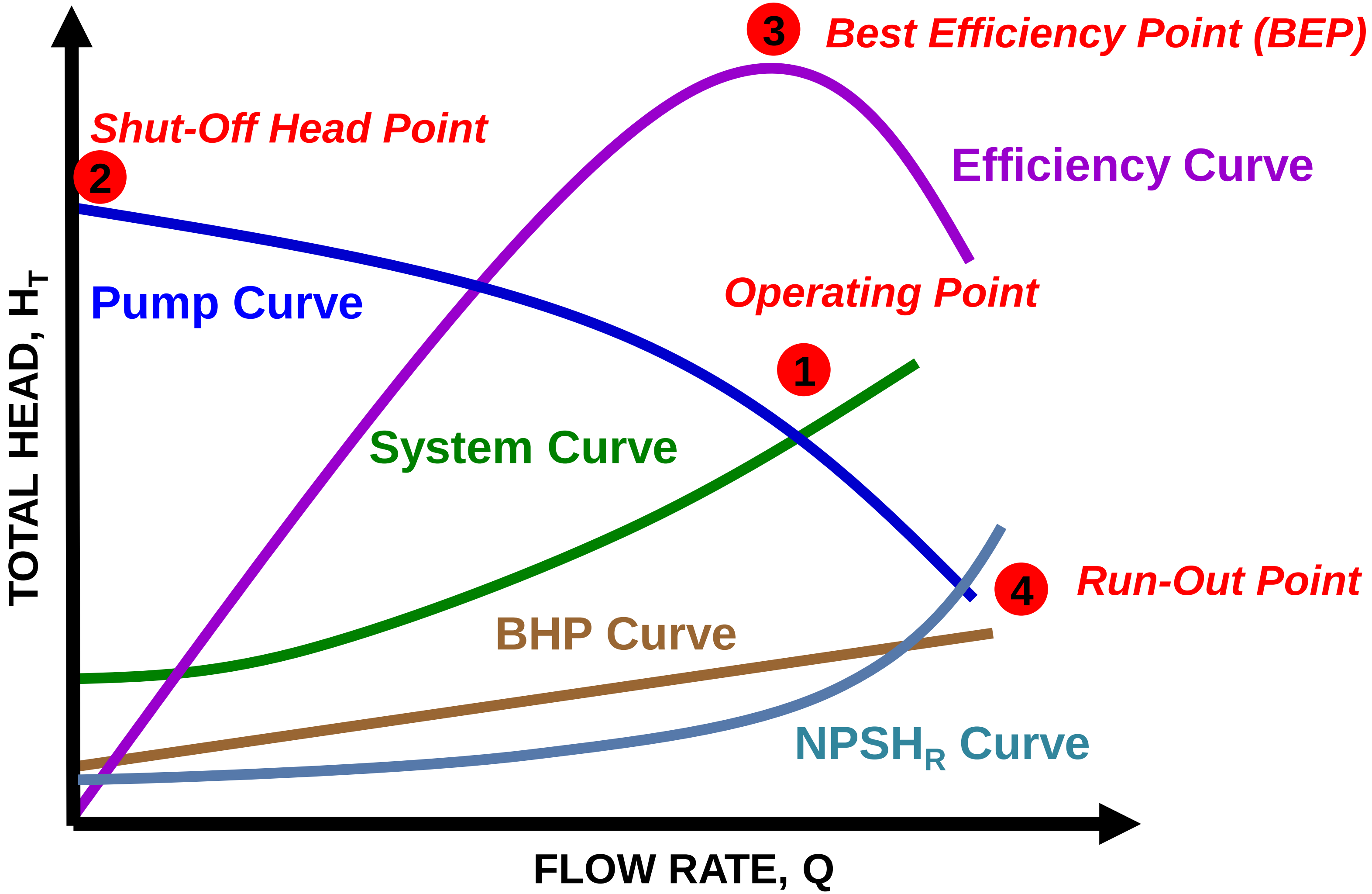
Total Flow gpm	TDH ft	NPSHa ft	Kf*Q^1.85 Friction Losses	Km*Q^2 Form Losses
0	296.42	33.99	0.00	0.00
250	297.03	33.97	0.34	0.27
500	298.73	33.89	1.24	1.07
750	301.45	33.76	2.62	2.42
1000	305.17	33.58	4.46	4.30
1250	309.87	33.36	6.73	6.72
1500	315.53	33.08	9.44	9.67
1750	322.13	32.76	12.55	13.17
2000	329.68	32.39	16.07	17.20

Minor Losses in Pipe Reach -- Pump 1

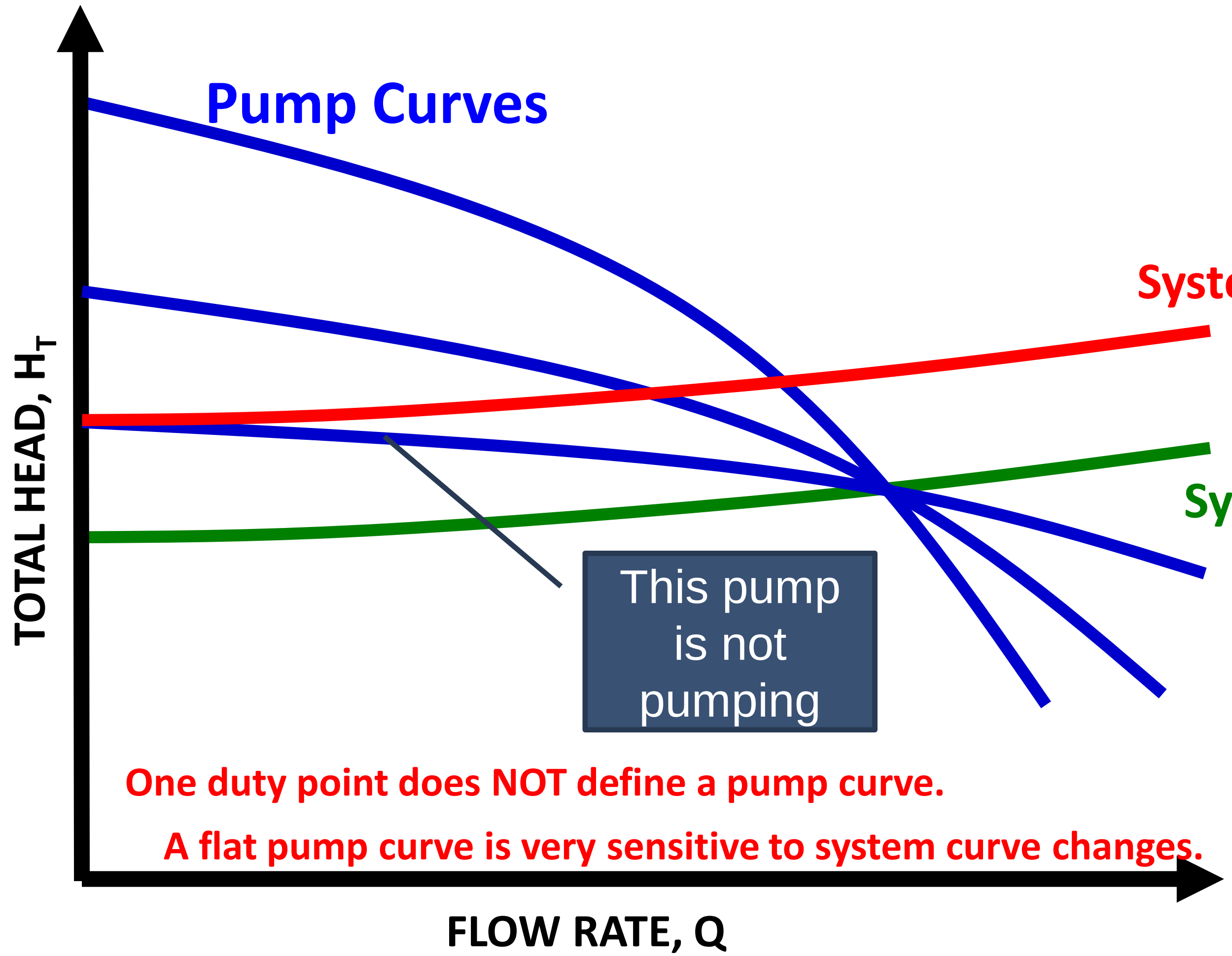
A. Suction-10" inside PS	
Minor loss type	K-value
slightly rounded entrance	0.23
gate valve	0.19
90° elbow	0.3
10x5" reducer	0.25
90° elbow	0.3
A. Subtotal	1.27



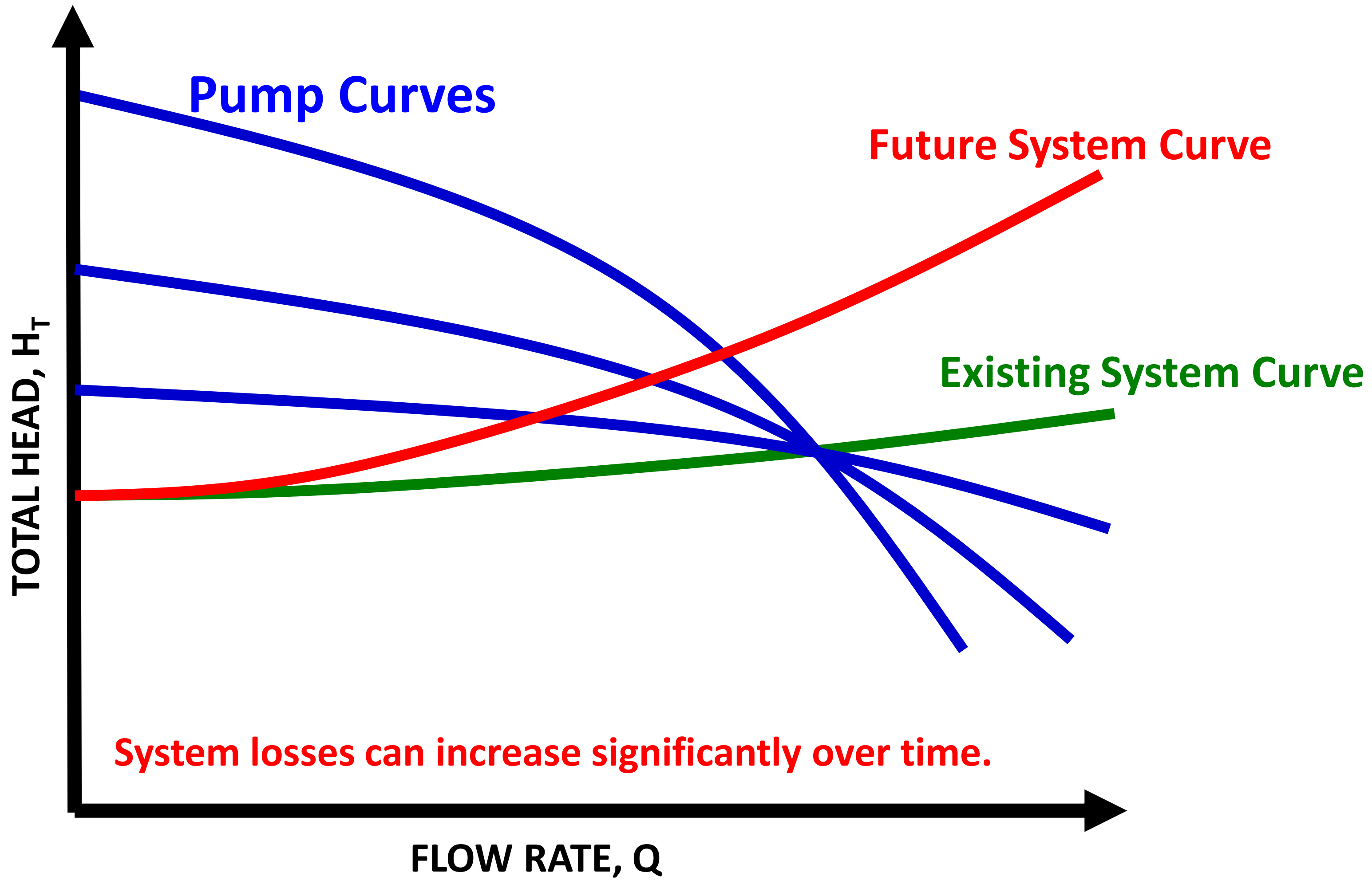
The Pump Curve



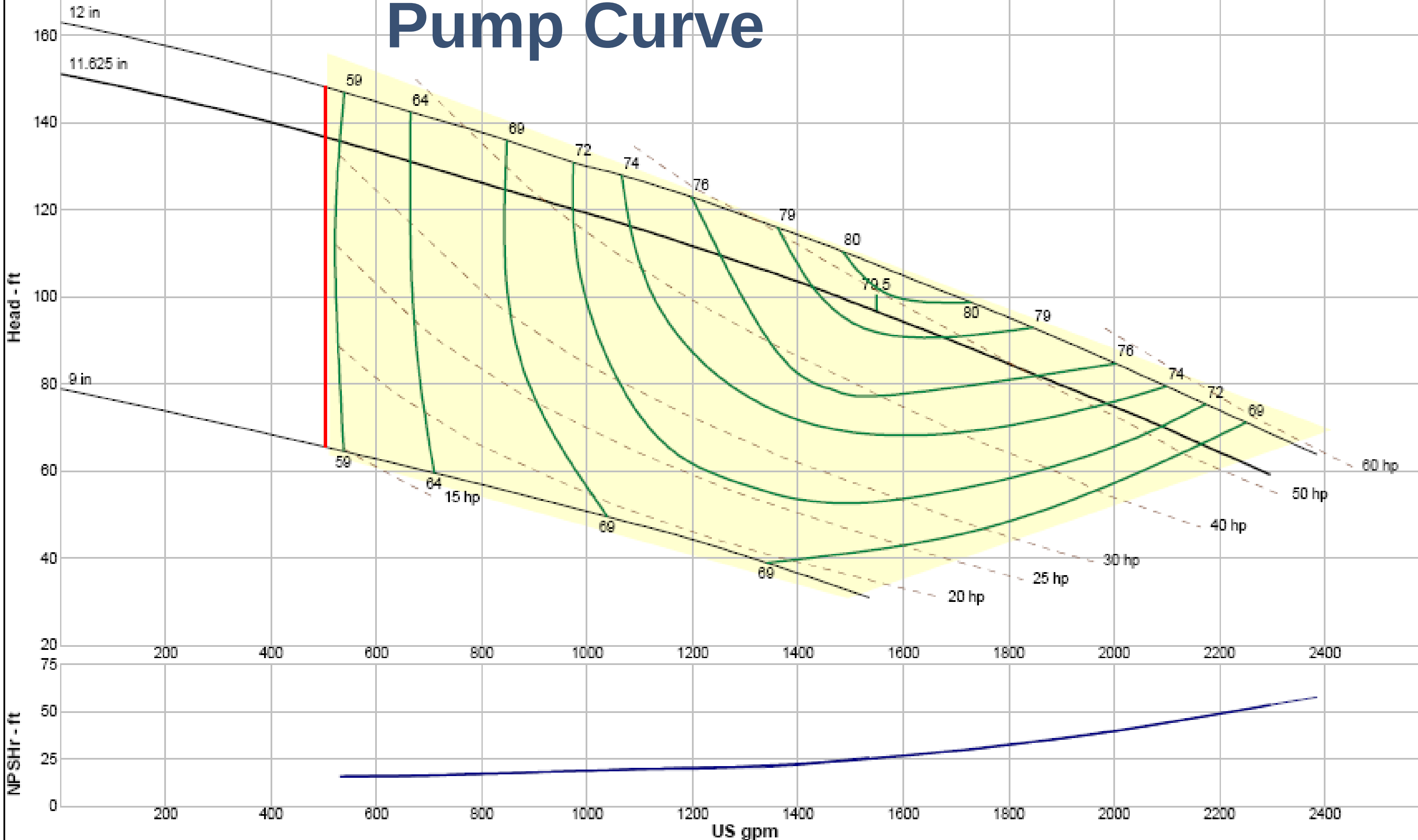
System Curve Envelope and Pump Curves



System Curve Considerations



Pump Curve



Curve efficiencies are typical. For guaranteed values, contact Fairbanks Morse or your local distributor. Las eficiencias en curvas son típicas. Para valores garantizados contacte a Fairbanks Morse o a su distribuidor local.

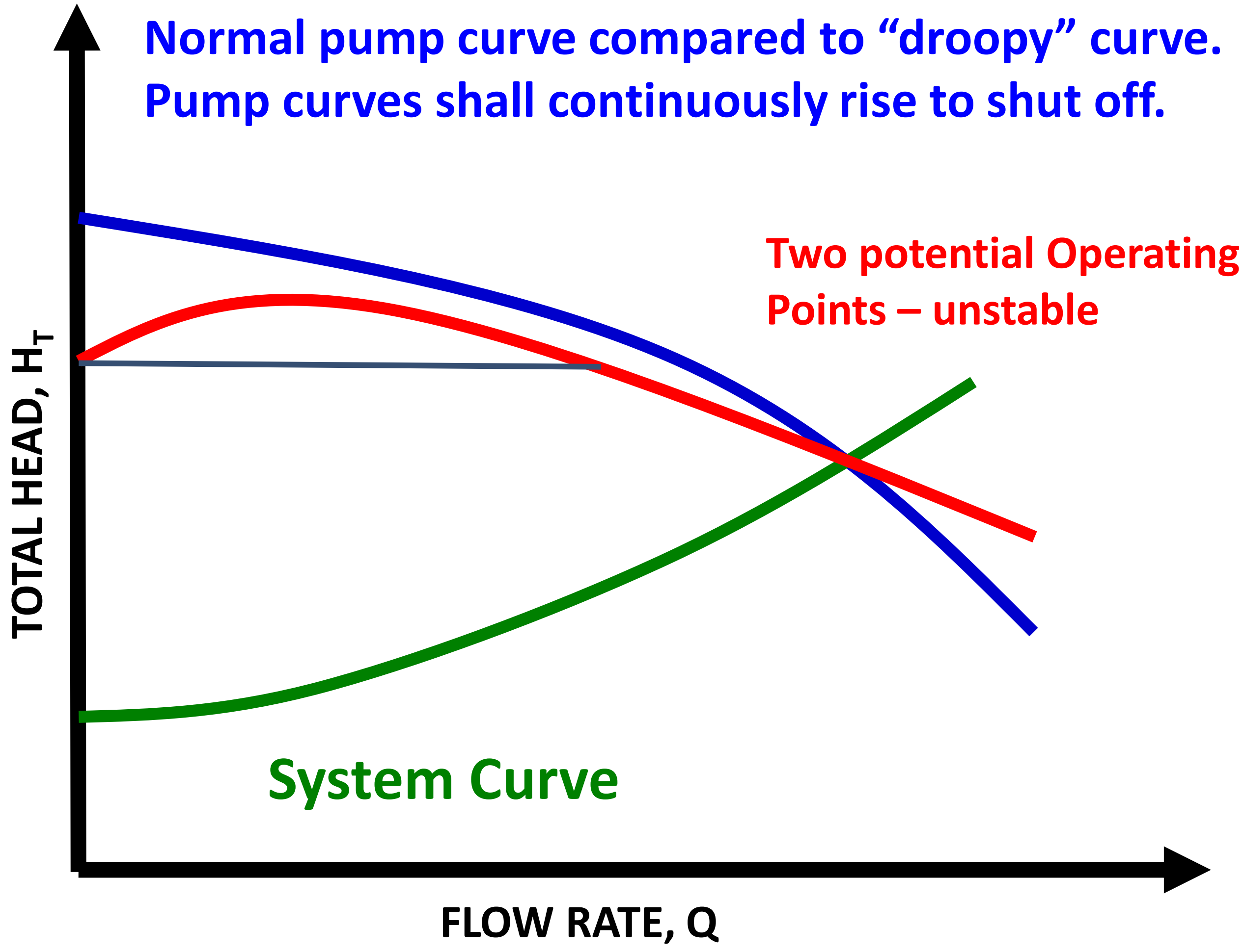
Company: Hazen and Sawyer
Name:
6/24/2010

Fairbanks Morse Pump, 60 Hz
Catalog: Fairbanks Morse Centrifugal.60, Vers 3
5400-NONCLOG - 1800

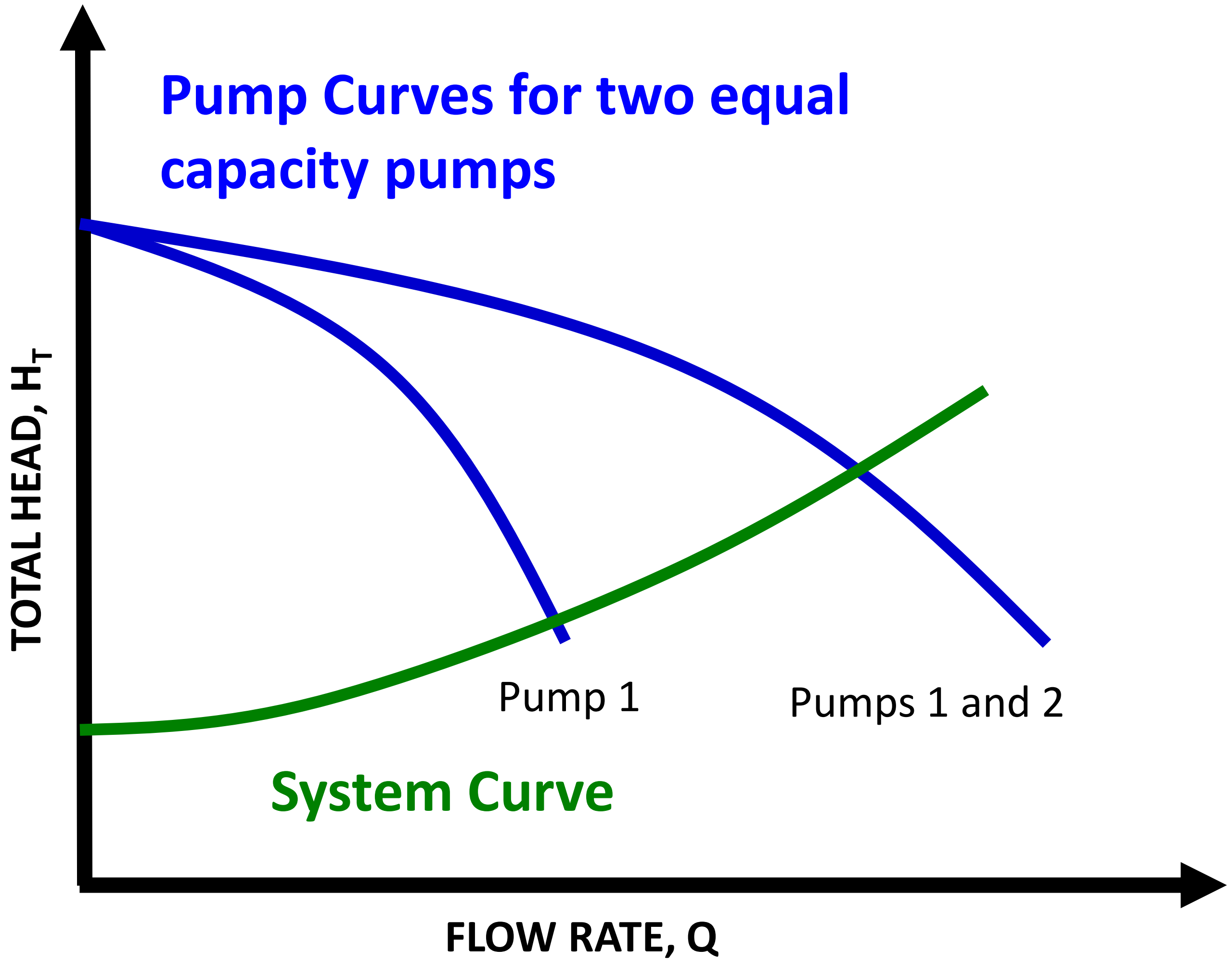
Size: 5"5413
Speed: 1780 rpm
Dia: 11.625 in
Curve: 130504A
Impeller: T5C1A

Fairbanks Morse
Pentair Water

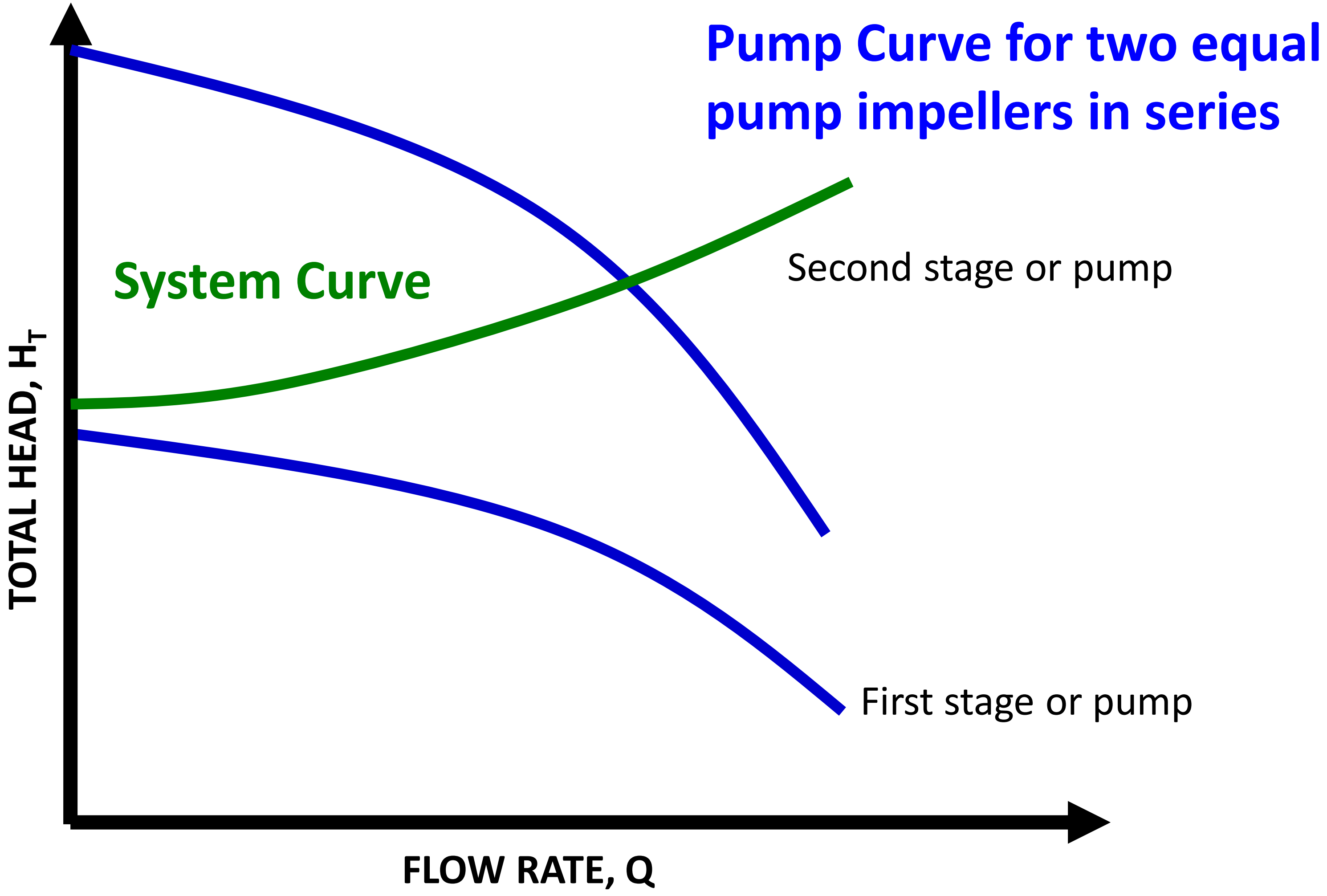
"Droopy" Pump Curves



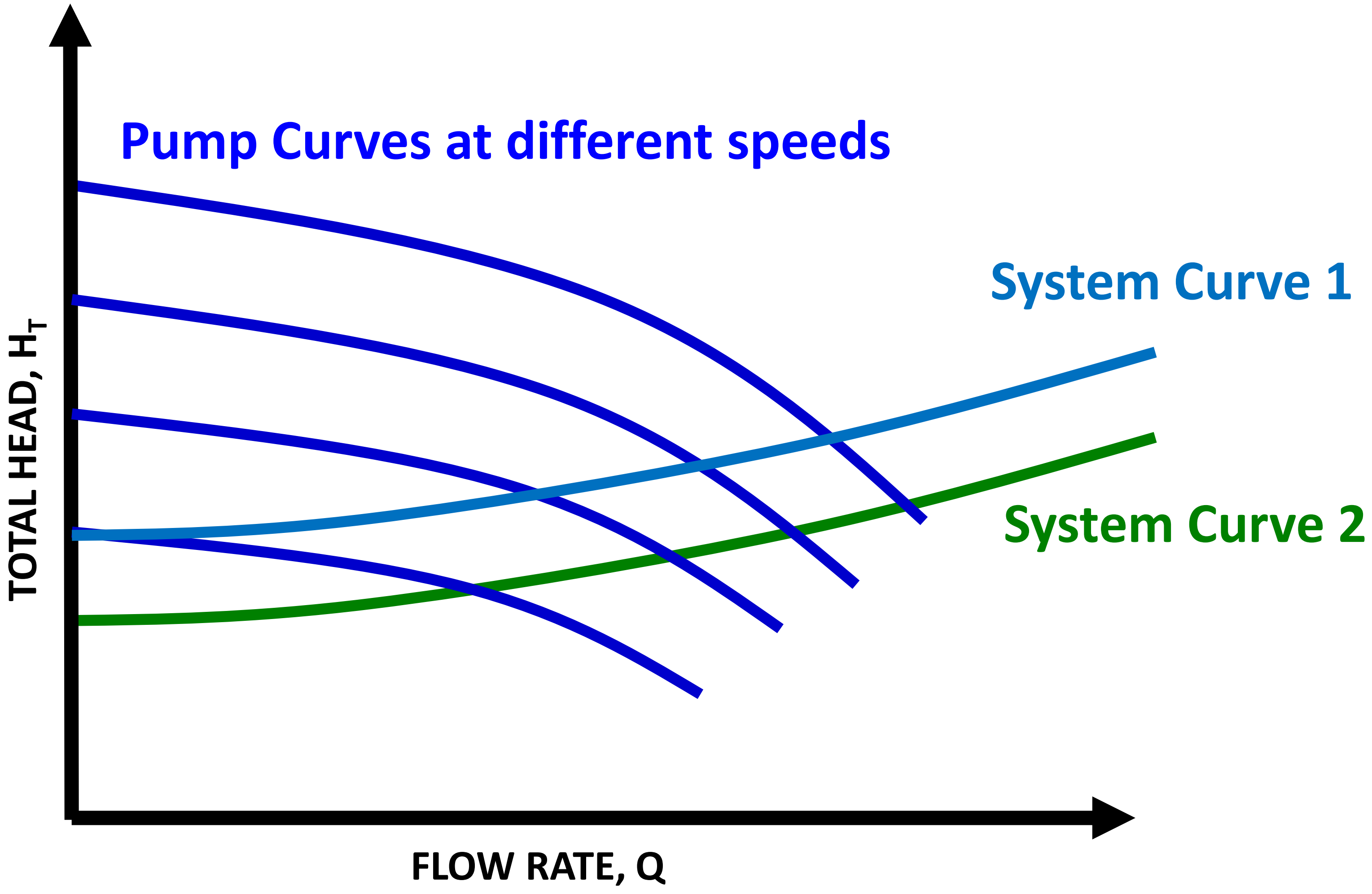
Curves – Pumps in Parallel



Curves – Pumps in Series



Curves – Pumps with Variable Frequency Drives (VFD)



Affinity Laws - Variable Speed

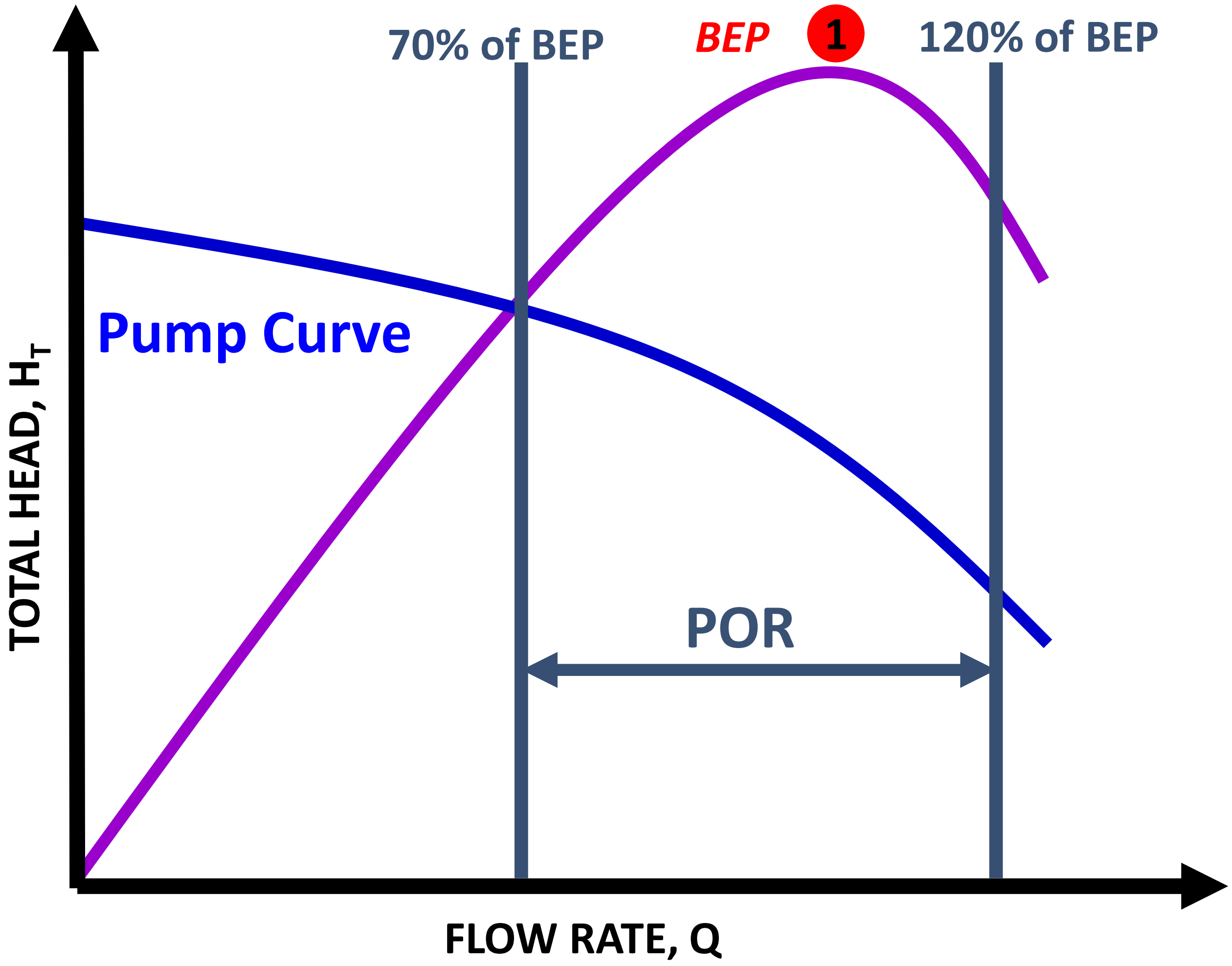
$$Q2 = Q1 * \frac{N2}{N1}$$

$$H2=H1 * \left[\frac{N2}{N1}\right]^{2}$$

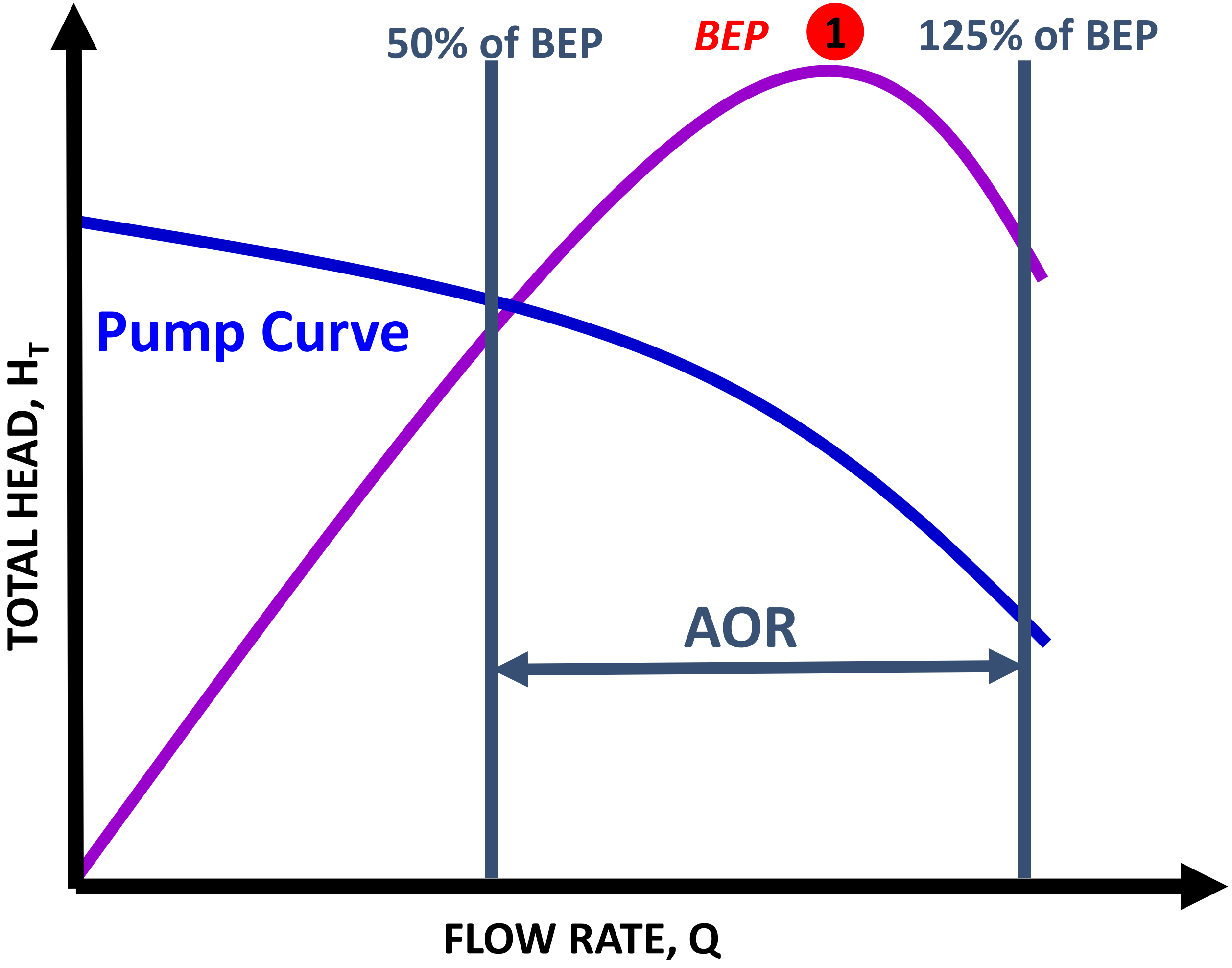
Manufacturer Pump Curves

Goulds 3316 6x8-17			Adjusted Pump Curves									
1786	Curve Speed		95.0	% Speed	90.0	% Speed	85.0	% Speed	80.6	% Speed	75.0	% Speed
17.00	Max Impeller		1697	RPM	1607	RPM	1518	RPM	1440	RPM	1340	RPM
14.25	Curve Impeller											
gpm	TDH	Efficiency	gpm	TDH	gpm	TDH	gpm	TDH	gpm	TDH	gpm	TDH
1,560	397	69	1,482	358	1,404	322	1,326	287	1,257	258	1,170	223
1,500	412	71	1,425	372	1,350	334	1,275	298	1,209	268	1,125	232
1,400	437	74	1,330	394	1,260	354	1,190	316	1,128	284	1,050	246
1,300	457	76	1,235	412	1,170	370	1,105	330	1,048	297	975	257
1,200	477	76	1,140	430	1,080	386	1,020	345	967	310	900	268
1,100	492	76	1,045	444	990	399	935	355	887	320	825	277
1,000	507	75	950	458	900	411	850	366	806	329	750	285
900	520	73	855	469	810	421	765	376	725	338	675	293
800	532	70	760	480	720	431	680	384	645	346	600	299
700	542	66	665	489	630	439	595	392	564	352	525	305
600	552	62	570	498	540	447	510	399	484	359	450	311
500	560	56	475	505	450	454	425	405	403	364	375	315
400	567	49	380	512	360	459	340	410	322	368	300	319
300	572	40	285	516	270	463	255	413	242	372	225	322
200	577	30	190	521	180	467	170	417	161	375	150	325
100	582	18	95	525	90	471	85	420	81	378	75	327
0	587	-	0	530	0	475	0	424	0	381	0	330

Preferred Operating Range

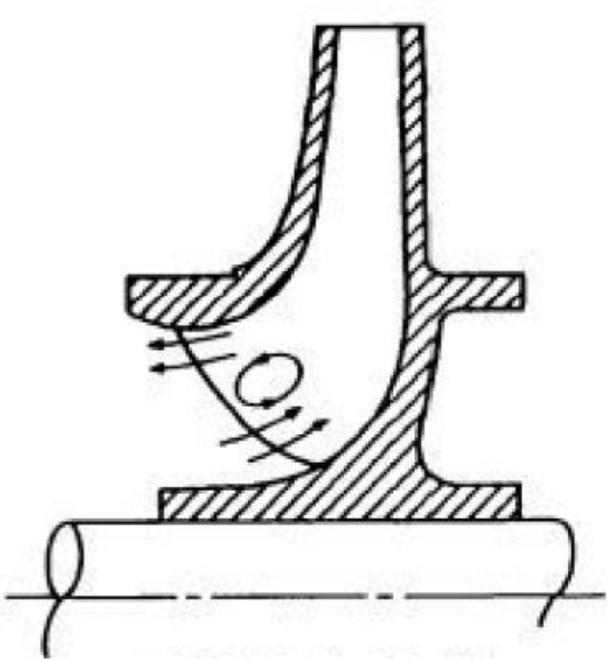


Allowable Operating Range



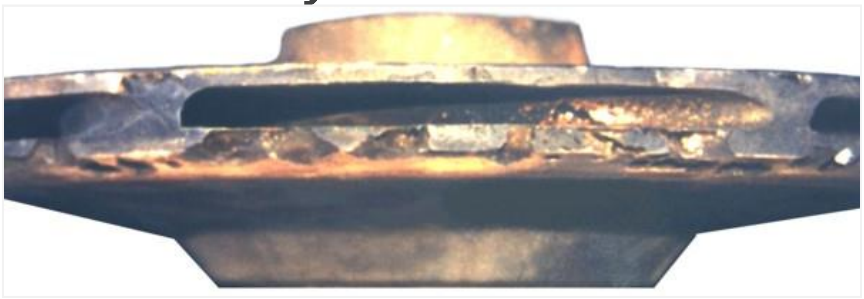
Operating Outside of POR/AOR

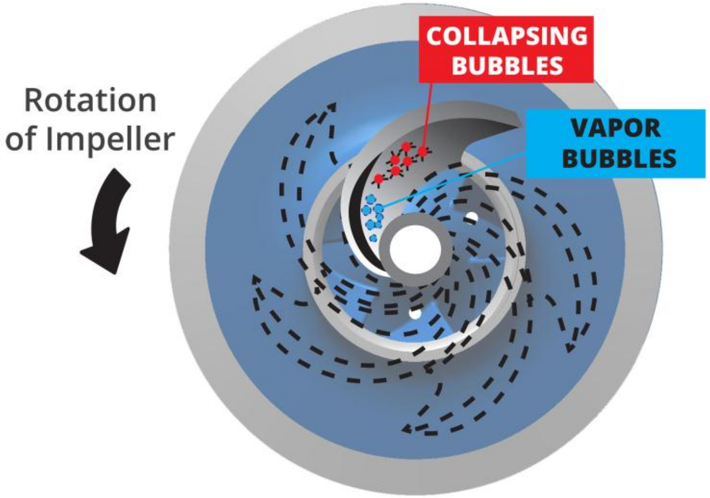
- Several issues occur when operating outside these ranges:
  - Recirculation
  - Excessive Noise
  - Excessive Vibration
  - Cavitation
  - Pump Damage



Cavitation Issues

- Results when liquid is subject to rapid changes of pressure that cause the formation of cavities where pressure is relatively low
- The formation and collapse of cavities or gas pockets can cause mechanical damage to impeller
- Accompanied by loud noises
- Caused by insufficient NPSH





Net Positive Suction Head (NPSH) – Avoiding Cavitation

- $NPSH_A$ – Total suction head available at the pump inlet

  $NPSH_A = h_{atm} + h_{ss} + h_{vs} - h_l - h_{vap}$

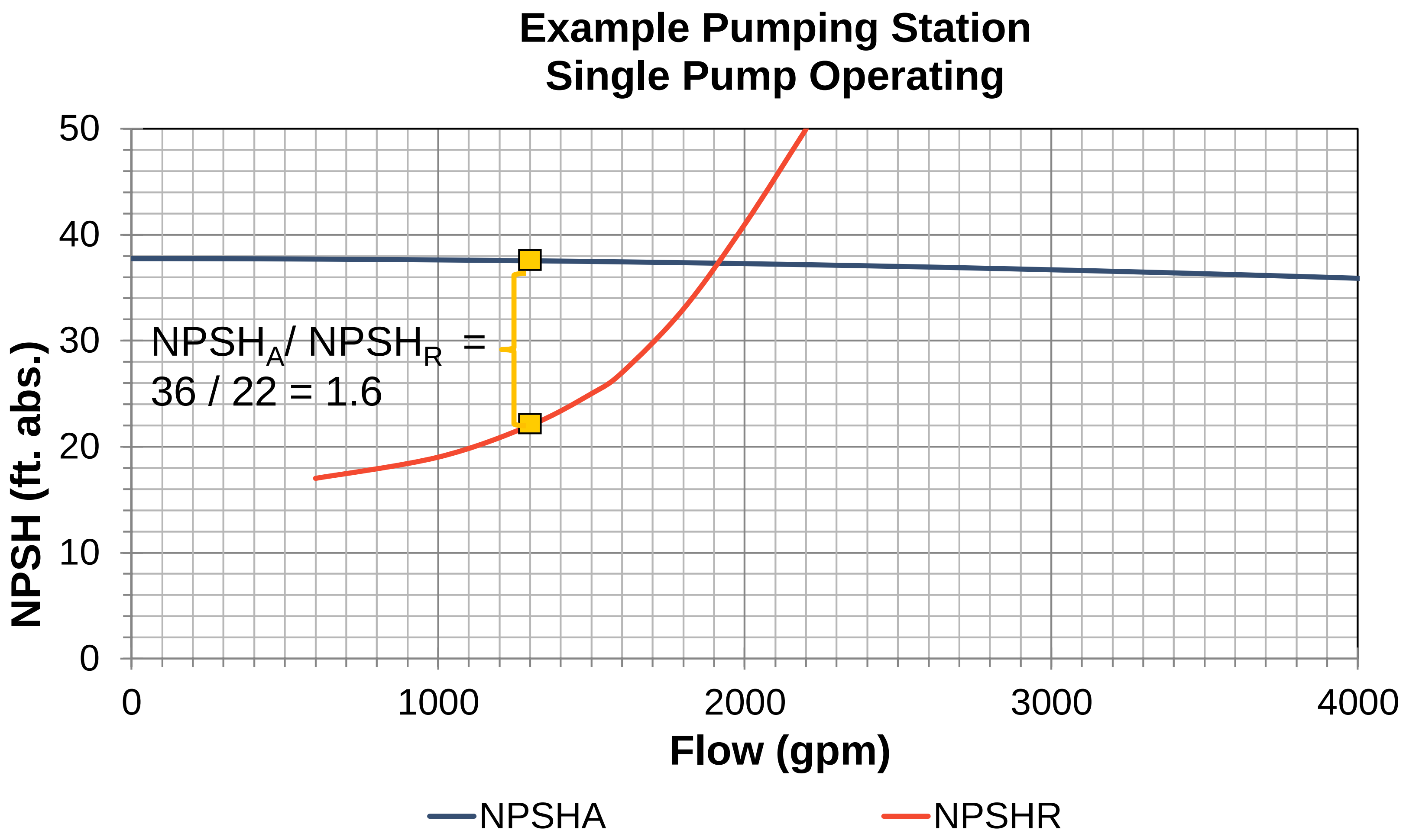
  Where:

  - h_{atm} = atmospheric pressure head (~34 ft)
  - h_{ss} = static suction head
  - h_{vs} = suction velocity head ($v^2/2g$)
  - h_l = headloss (friction + minor losses) in suction piping
  - h_{vap} = vapor pressure head of liquid being pumped (table lookup based on pressure, temp – Ex. 1.18 ft. for water at 1 atm and 80° F)

- $NPSH_R$ – net positive suction head required, as published by manufacturer
  - Defined by HI as the NPSH that causes the total head of the pump (or 1st stage of pump if multi-stage) to be reduced by 3% at a specific rate of flow

- NPSH Margin ($NPSH_A$/ $NPSH_R$) – 1.1 to 2.0 (ANSI/HI)

Example of $NPSH_A$/ $NPSH_R$



Correcting NPSH Problems

- Increase wetwell level or supply pressure
- Lower pump elevation
- Reduce headloss in suction piping
  - Check for blockages in pipe
  - Ensure that valves are operating correctly
  - Increase diameter of suction piping
  - Use long-radius bends
- Select (or run at) a lower speed pump
- Choose pump with larger suction diameter

Water Hammer

- Also known as hydraulic shock or surge
- An oscillation in pressure resulting from a rapid increase or decrease in flow (stopping pump, closing valve)
- Causes serious mechanical damage and loud noises
- Surge valves can help minimize water hammer

Water Hammer

Joukowsky head change:

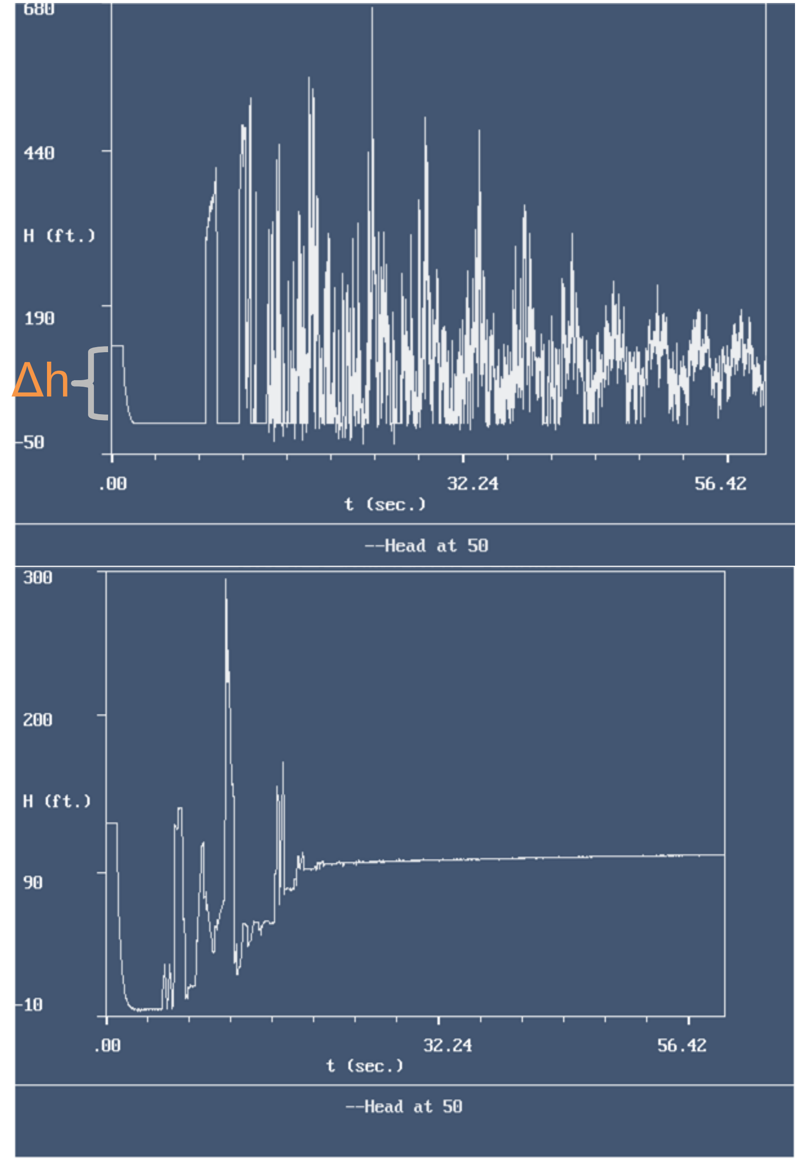
$$\Delta h = \frac{c}{g} * \Delta v$$

where c = wave propagation speed in pipe material

g = acceleration due to gravity

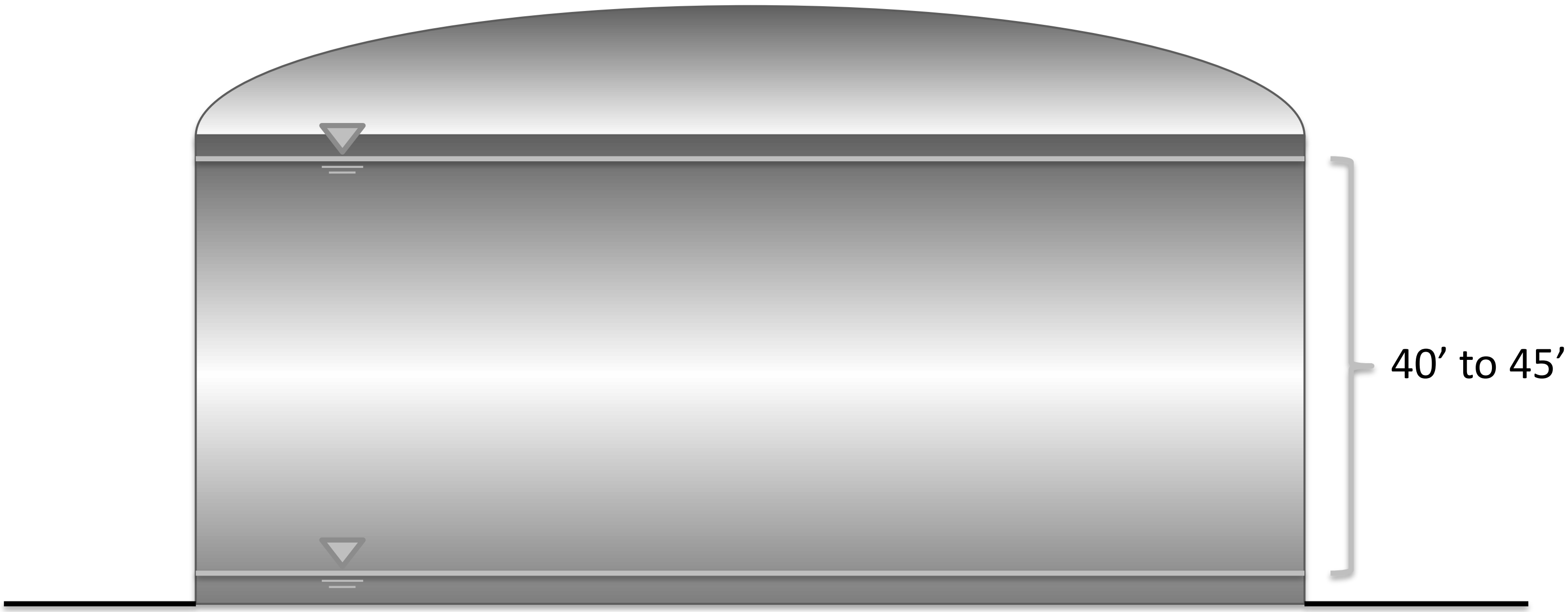
Δv = change in flow velocity

- Occurs most often due to power failure (pump trip)
- Mitigation methods: surge tanks, damped check valves, surge relief valves, air inlet (vacuum relief) valves



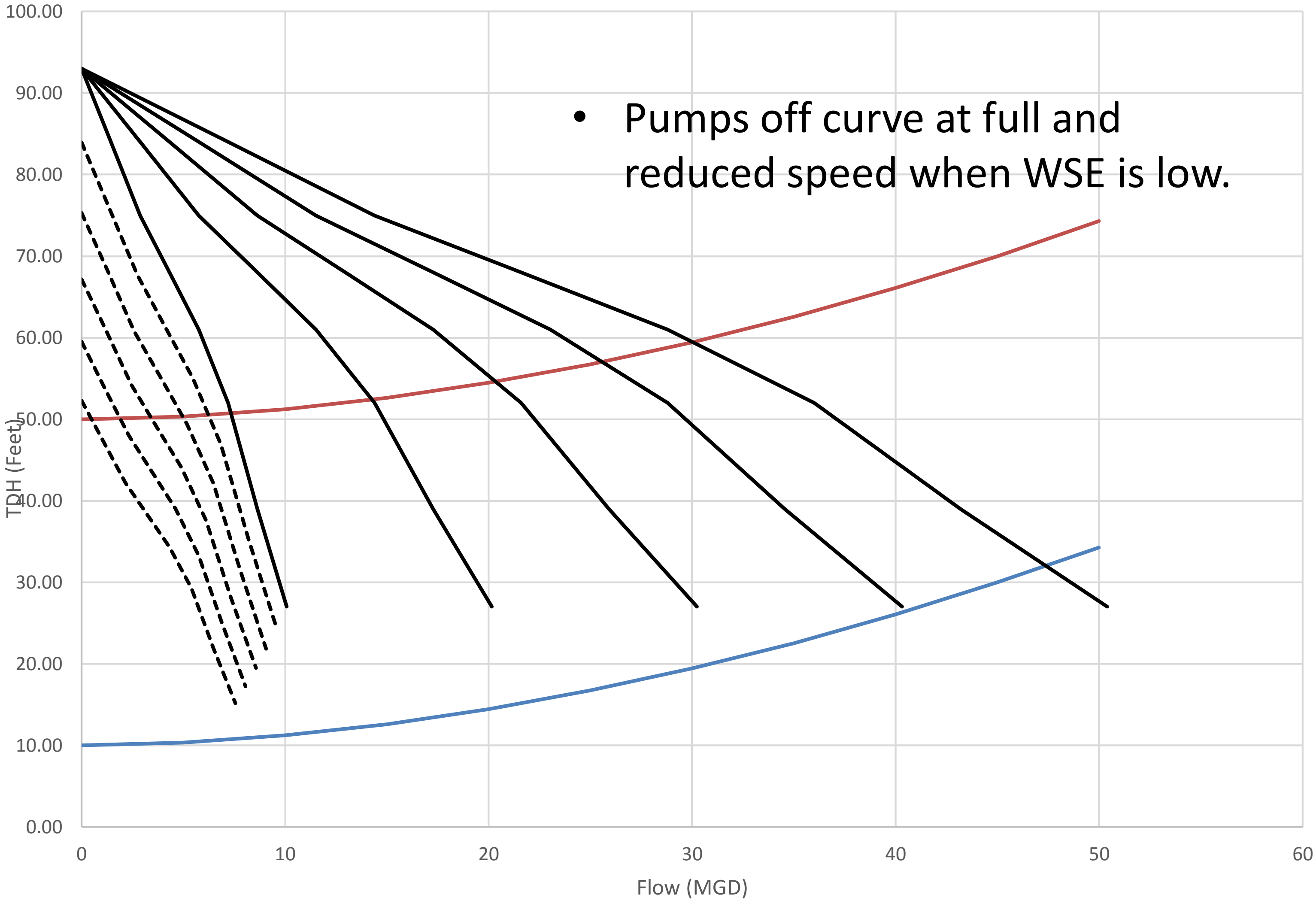
Case Study – Flow Equalization Basin

- Prestressed Concrete Ground Storage Tank
- Pumped Influent, Gravity Drain
- Varying Water Levels Pose Hydraulic Challenges

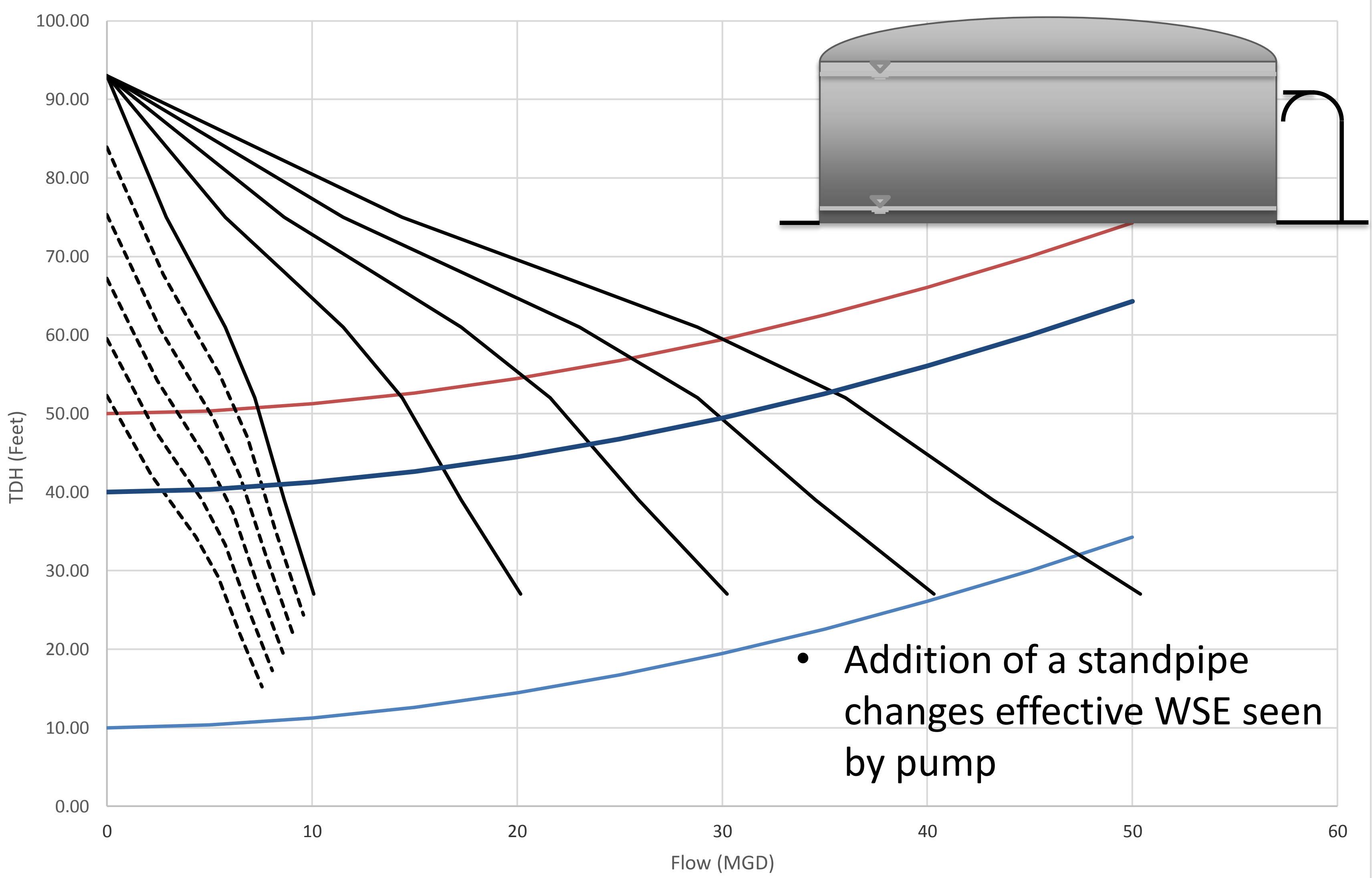


Case Study – Flow Equalization Basin

- Pumps off curve at full and reduced speed when WSE is low.



Case Study – Flow Equalization Basin



- Addition of a standpipe changes effective WSE seen by pump

Case Study – DC Water Blue Plains FADF FIP System

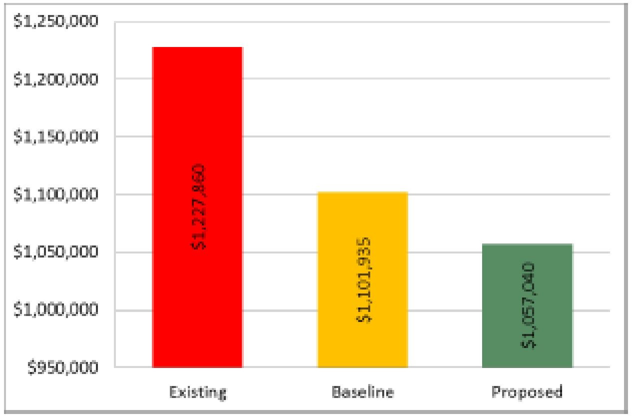
- (10) 100 MGD Vertical Turbine Pumps
  - Magnetic Drives limit to 90% turndown
  - Insufficient Submergence
  - Pumps, motors and mag drives at end of life
- Slamming of check valves
  - Undersized air and vacuum valves
- Proposed System:
  - (10) 70 MGD Constant Speed Pumps
  - (2) 50 MGD Pumps (VFD's)
  - Premium Efficiency Motors
  - New Medium Voltage Electrical Facility
- Increase in Forebay WSE
  - Floating Datum Concept
- Refine Control Strategy

FIP System – Energy Savings

- Replacement Pumps, Motors and Controllers
- Proposed Control Strategy
- Trial by locking Mag Drives at 100% with FIP 11 and 12 as trim pumps
- Operational Changes:
  - Discharge to FIC – WSE at 26’
  - Increase Forebay WSE – Floating Datum concept
  - Datum a function of influent flow and headloss

	FADU Phase 2 Basis of Design			FIP Alternative Analysis Basis of Design		
Flow Condition	FIP Q (mgd)	Recycle Flow (mgd)	Forebay Operating Range (elev)	FIP Q (mgd)	Recycle Flow (mgd)	Forebay Operating Range (elev)
Peak Influent	740	110	-1 to +3	555	110	+1 to X
Average Influent	370	20	-1 to +3	330	20	+1 to X
Minimum Influent Flow	180	0	-1 to +3	180	0	+1 to X

FIP System Annual Energy Cost



- Energy savings of approx. $160,000 / year

Case Study – DC Water Blue Plains RWWPS2

- (9) 100 MGD Split Case Centrifugal Pumps
- Rehabilitate for 20 year design life
  - On site repairs
  - Off site rehabilitation
  - Allowance for unanticipated work
  - Motor replacement
  - Controller replacement
- Rehabilitate Discharge Siphons
  - Design point correction
  - Energy Savings
- Refine Control Strategy

RWWPS 2 - Discharge Siphon Improvements

- Rehabilitation of pumps and operation of the wet well at a higher WSE alleviates need for vacuum priming system

- Restore siphon operations – 12” vent
  - Discharge check valve
  - Vacuum breaking valve

- Corrects the pumps primary operating point

- Provides for energy savings
  - 4’ high point
  - PCS data shows ADF of 165 MGD
  - Wire to water efficiency of 70%
  - Energy cost $0.09/kWh
  - Approximately $100,000 / year in consumption

Summary – Pump and System Curves

- There will be several system curves – explore all boundaries – low and high flow / elevations, existing and future C-factors
- Use real elevations for system curves (not pump TDH)
- Avoid flat pump curves if VFDs to be used
- Use affinity laws to explore speed impacts
- Duty point to be ~75% Q_{max}, close to BEP
- Aim for efficiencies > 75% single stage

Summary - Centrifugal Pump Selection

- Single duty point is insufficient to specify pump
- Give secondary points for VFD reduced speed curves
- No droopy curves – unstable operation - “shall continuously rise to shut off”
- Size motors for Run Out / Maximum HP
- Make sure pump motors are inverter-rated if using VFDs
- Pump motors can be noisy and generate heat (VFDs too)

Summary - Good Hydraulic Design

- Develop system curves early
- Get real data – measure, survey, test
- Follow HI Standards
- The best flow path is a smooth one
- Don't forget NPSH – no cavitation!
- Consider surge pressure in design
- Consider the full range of possible operating conditions, now and future
- Provide flexibility and expandability
- Work with vendors and O&M staff
- Iterative process

Acknowledgements / Useful Web Sites

- Hydraulic Institute Standards – www.pumps.org

- Books: Pumping Station Design – Sanks, Perry's Chemical Engineers' Handbook, Cameron Hydraulic Data, etc.

- Other useful websites:
  - www.pump-zone.com
  - www.pumped101.com
  - www.mcnallyinstitute.com
  - www.pumpcalcs.com
  - www.eere.energy.gov
- Hazen colleagues - Brian Porter, Bryan Lisk and Ellen Hall, among others

Questions?

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