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Fundamentals Of Water Hammer And Surge Suppression

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Dynamic solutions for a fluid world ™

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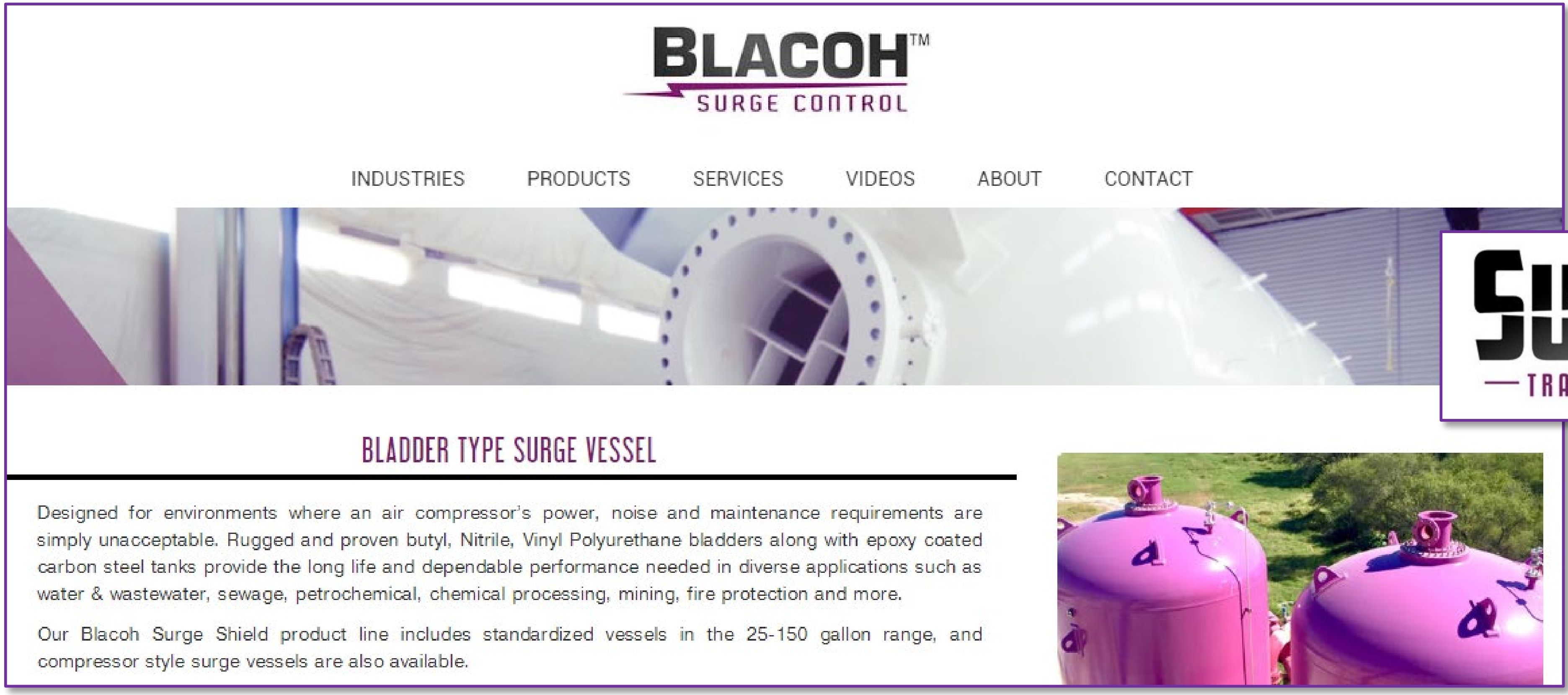
Executive Vice President at **Blacoh** Industries. Well-respected trailblazer in fluid dynamics with three decades of academic, design and application experience. Expert on surge control. Specialties include pump station/pipeline design and computer modeling, piping components, instrumentation, and electrical control panel design.

Applied Flow Technology

26	40	80+	700+	25,000+
Years in Business	Channel Partners	Countries	Fluids in our database	Engineers use AFT Software

- *AFT Impulse*™ – Commercial waterhammer simulation software since 1996
- World leader in fluid system software solutions



SURGEWAVE™
TRANSIENT MONITORING SYSTEM

- BLACOH – Surge and pulsation vessel manufacturer since 1976
- World leader in surge suppression and monitoring solutions

Agenda

- Waterhammer Overview
  - Accidents
  - Codes & Standards
  - Joukowsky Equation
  - Communication Time
  - Physics
  - Brief Discussion of Fundamental Equations
- Technical Questions Answered by Waterhammer Analysis
- Pumps
- Valves
- Check Valves
- Transient Cavitation
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  - Types of piping and wavespeed
  - Changing component behavior
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Waterhammer Video

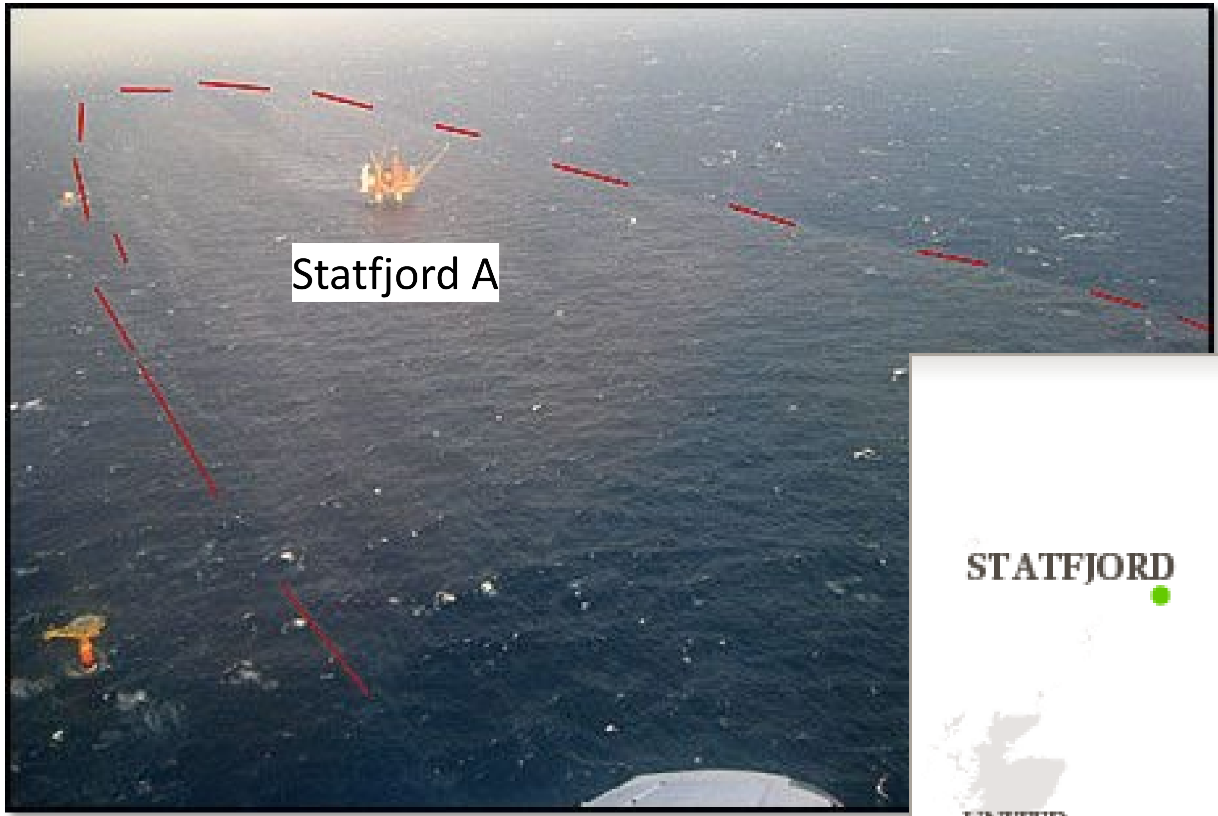
www.youtube.com/watch?v=oZbguheiVs4&NR=1

Waterhammer Accident 1 (2008): Burst Pipe on I-25 in Denver, Colorado, USA

- 66-inch pipeline burst due to waterhammer after pump failure

Waterhammer Accident 2 (2007): Burst Hose on Oil Loading, 2nd Biggest Spill in Norway

- Valve slam in 20” hose while pumping into tanker caused 27,500 barrels of crude spill



Codes and Standards for Waterhammer

- Little guidance exists from codes and standards on waterhammer
  - Engineers expected to use judgement and experience
- ASME B31.4:
  - "Surge calculations shall be made, and adequate controls and protective equipment shall be provided, so that the level of pressure rise due to surges and other variations from normal operations shall not exceed the internal design pressure at any point in the piping system and equipment by more than 10%."

Codes and Standards for Waterhammer (2)

- ASME B31.3:
  - "In no case shall the increased pressure exceed the test pressure used under para. 345 for the piping system." And "Occasional variations above design conditions shall remain within one of the following limits for pressure design: Subject to the owner's approval, it is permissible to exceed the pressure rating or the allowable stress for pressure design at the temperature of the increased condition by not more than 33% for no more than 10 hr at any one time and no more than 100 hr/yr or 20% for no more than 50 hr at any one time and no more than 500 hr/yr."
- A new ASME B31D waterhammer guideline is in development

Overview of Waterhammer

- Waterhammer is a transient phenomenon that occurs in a liquid piping system when some event causes a departure from steady state
- Waterhammer is the process the piping system experiences as it adjusts to the new conditions
- Waterhammer can be caused by many events including
  - Valve closure or opening (in full or in part)
  - Pump speed change
  - Relief valve cracking open
  - Tank pressurization
  - Periodic pressure or flow conditions

Terminology

- The term "waterhammer" confuses some because it implies a process only in water systems
- Other terms which have been used are
  - Fluidhammer
  - Hydraulic Transients
  - Fluid Transients
  - Surge

Instantaneous Waterhammer

- The magnitude of a waterhammer transient is dependent on the wavespeed of the liquid
- The wavespeed (*a*) is dependent on the:
  - liquid acoustic velocity
    - liquid density & liquid modulus of elasticity
  - pipe modulus of elasticity (*E*), wall thickness (*t*), and material Poisson Ratio (*μ*)
  - pipe restraints
- Common wavespeed for water in a carbon steel pipe
  - $a \approx 4{,}000$ ft/s (1,300 m/s)

Instantaneous Waterhammer (2)

- It can be shown that the maximum theoretical pressure surge is given by the instantaneous waterhammer equation, also known as the Joukowsky equation

$$\Delta P = -\rho a \Delta V$$

  - Example: Density is 62.3 lbm/ft3 (1000 kg/m3), Wavespeed is 3000 ft/sec (915 m/sec), Initial Velocity is 10 ft/sec (3 m/sec), Static Pressure is 100 psia (7 bar)

$$P_{max} = 62.3 \frac{lbm}{ft^3} * 3000 \frac{ft}{s} * 10 \frac{ft}{s} * \frac{1 ft^2}{144 in^2} * \frac{lbf - s^2}{32.2\ lbm - ft} + 100\ psia$$

$$P_{max} = 400 + 100\ psia = 28 + 7\ bar$$

$$P_{max} = 500\ psia = 35\ bar$$

  - Be careful with this equation, as it is often assumed to be conservative worst-case – it isn't
    - See "Walters and Leishear (2019)"

Communication Time

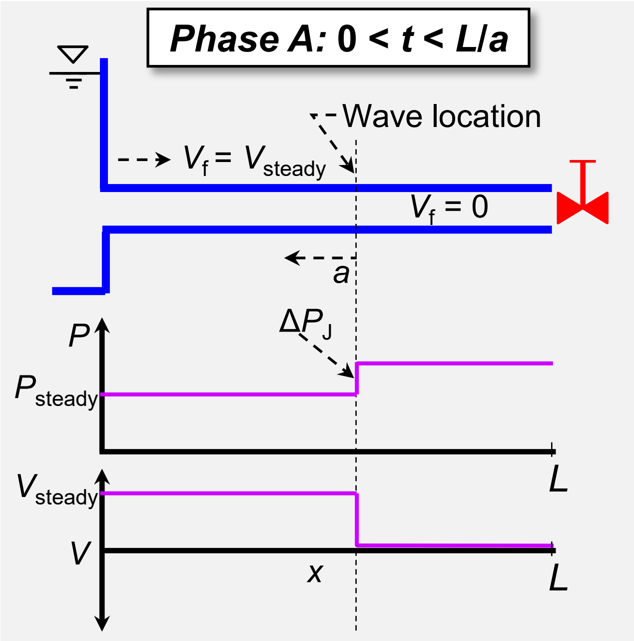
- The communication time is:
  - a helpful concept in understanding waterhammer
  - time for transient events to communicate their existence back to their point of origin
  - given by the following

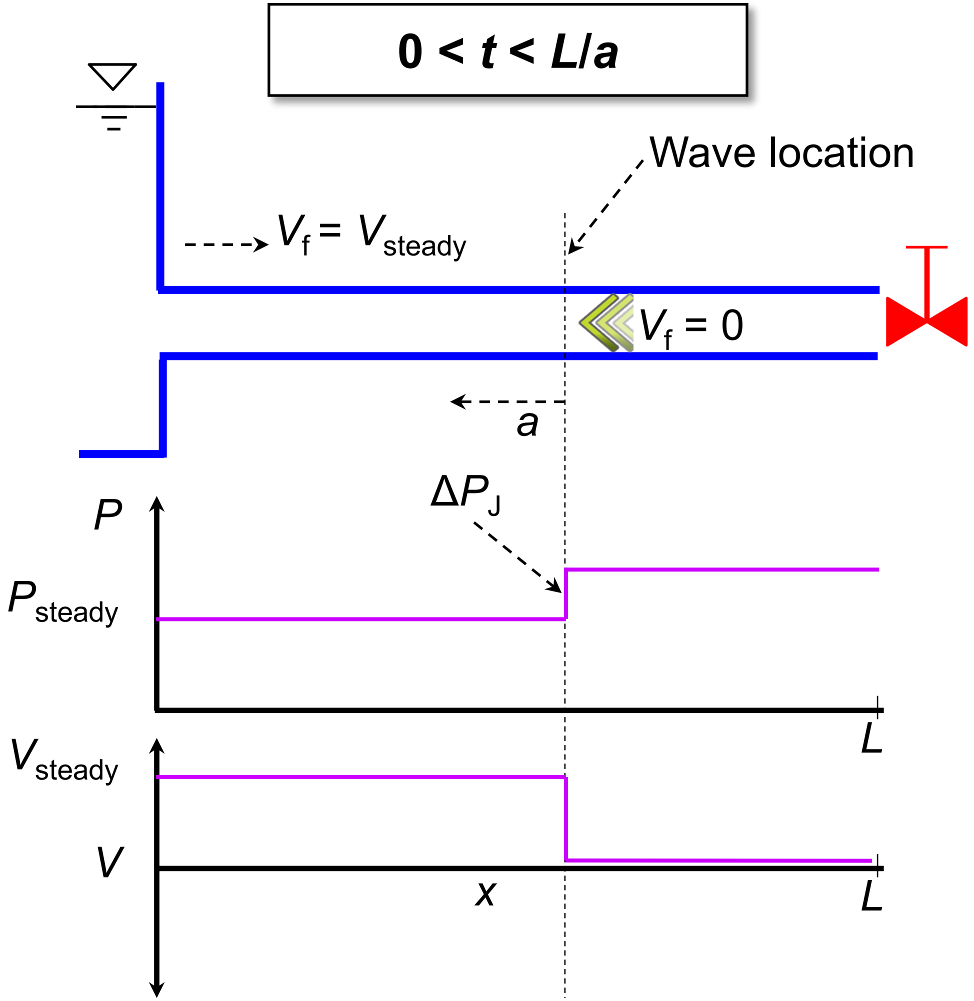
$$\Delta t = 2\frac{L}{a}$$

- Any event that occurs in a time frame less than the communication time is in effect instantaneous

a (wavespeed)		L (length)		t_c
ft/s	m/s	ft	m	sec
4000	1219	200	61	0.1
4000	1219	2000	610	1
4000	1219	20000	6100	10
4000	1219	200000	61000	100

Waterhammer Sequence, Instant Valve Closure: A B C D





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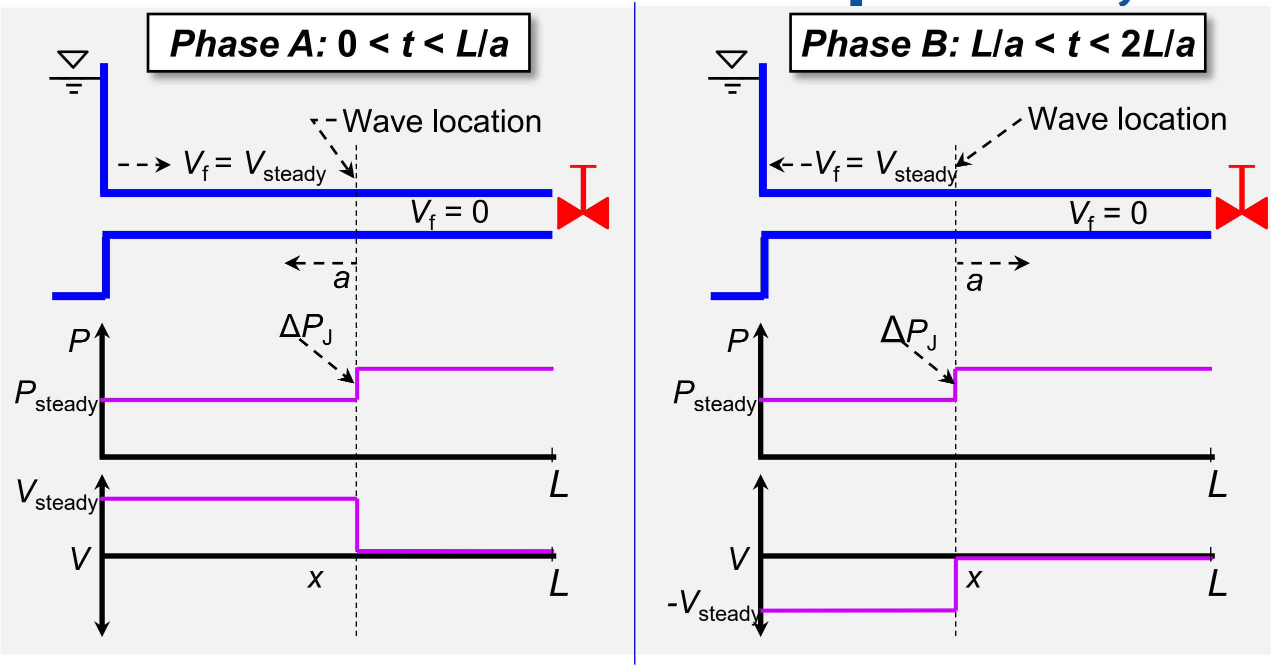

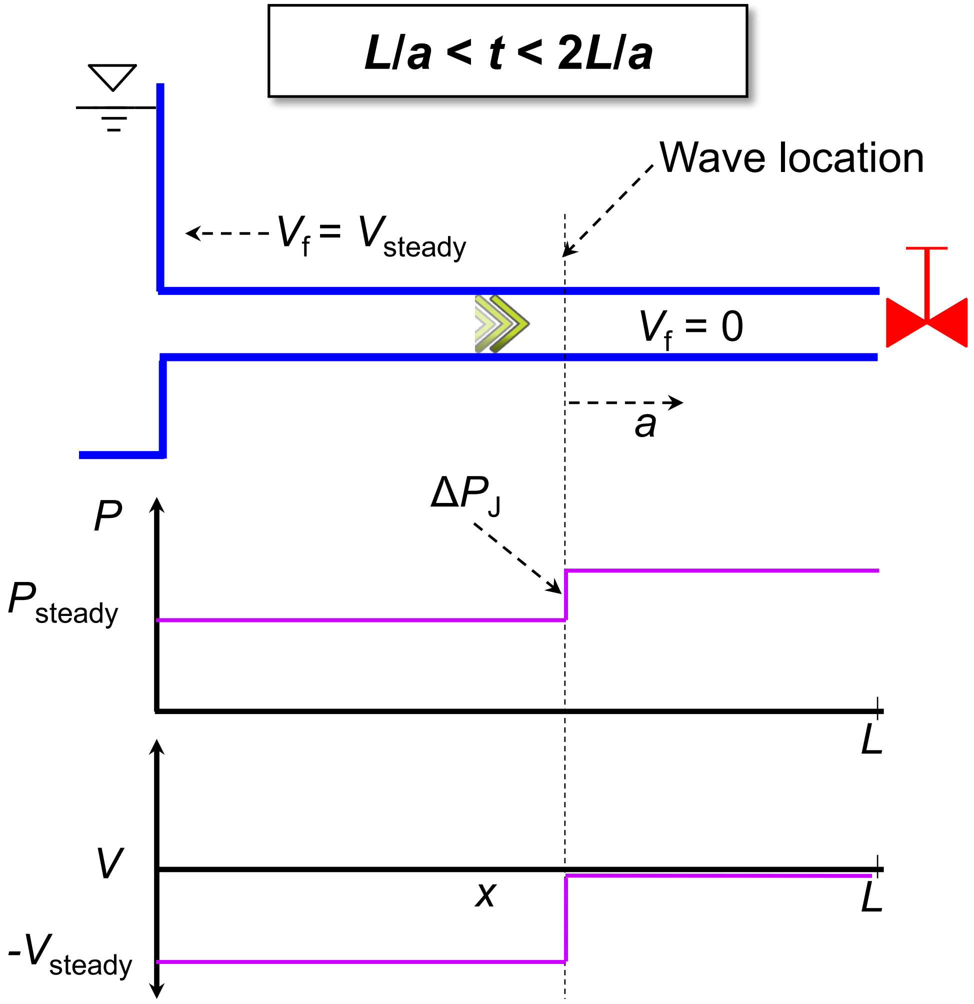

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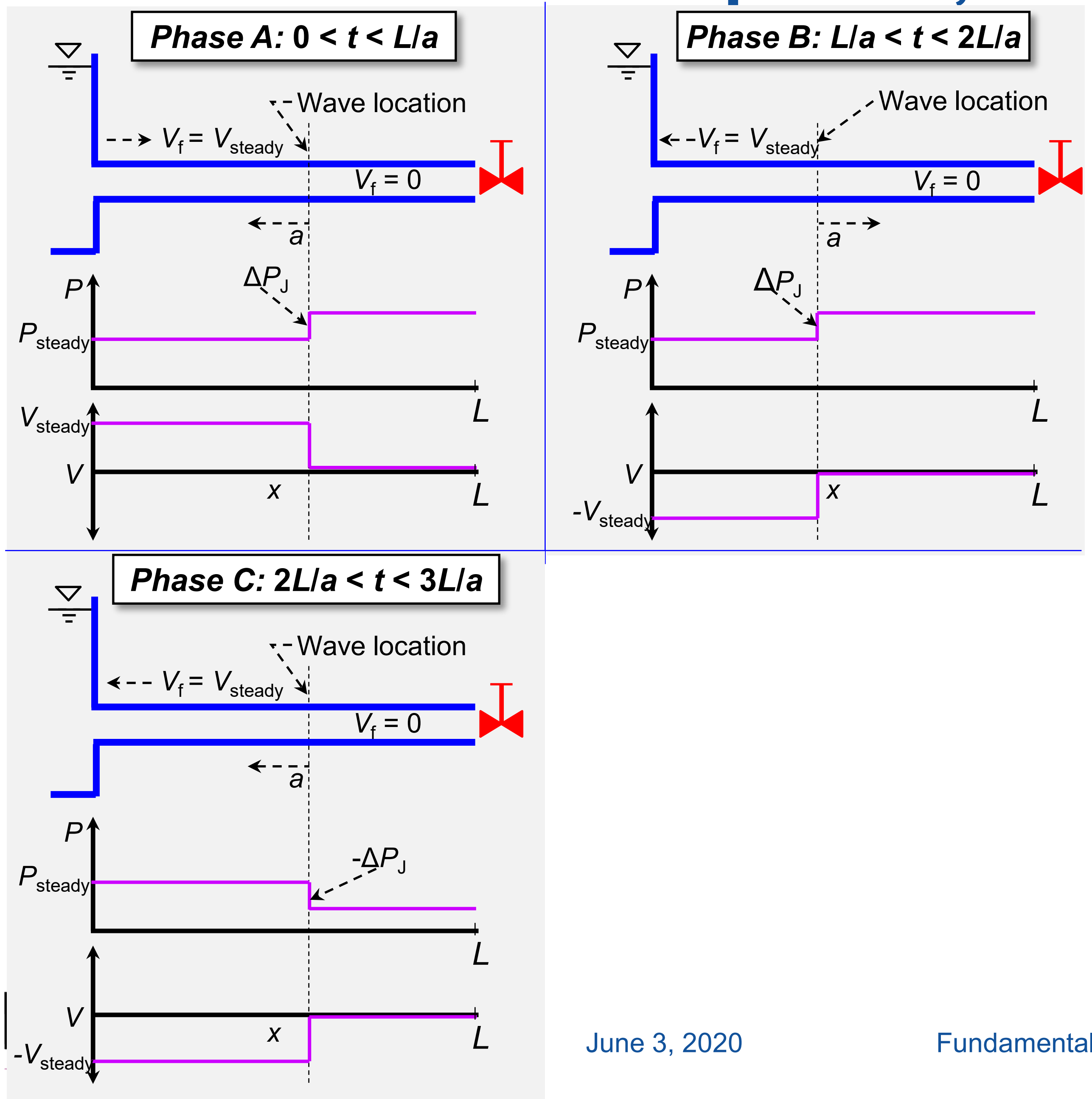

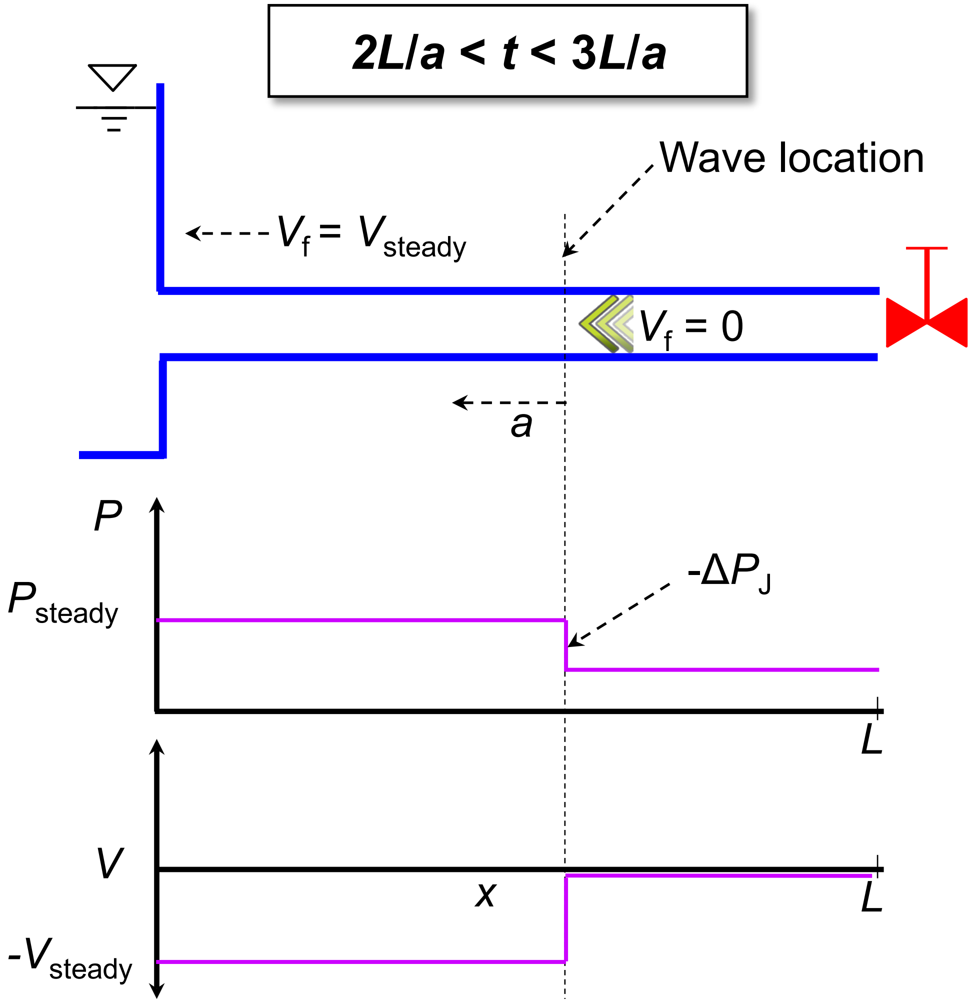

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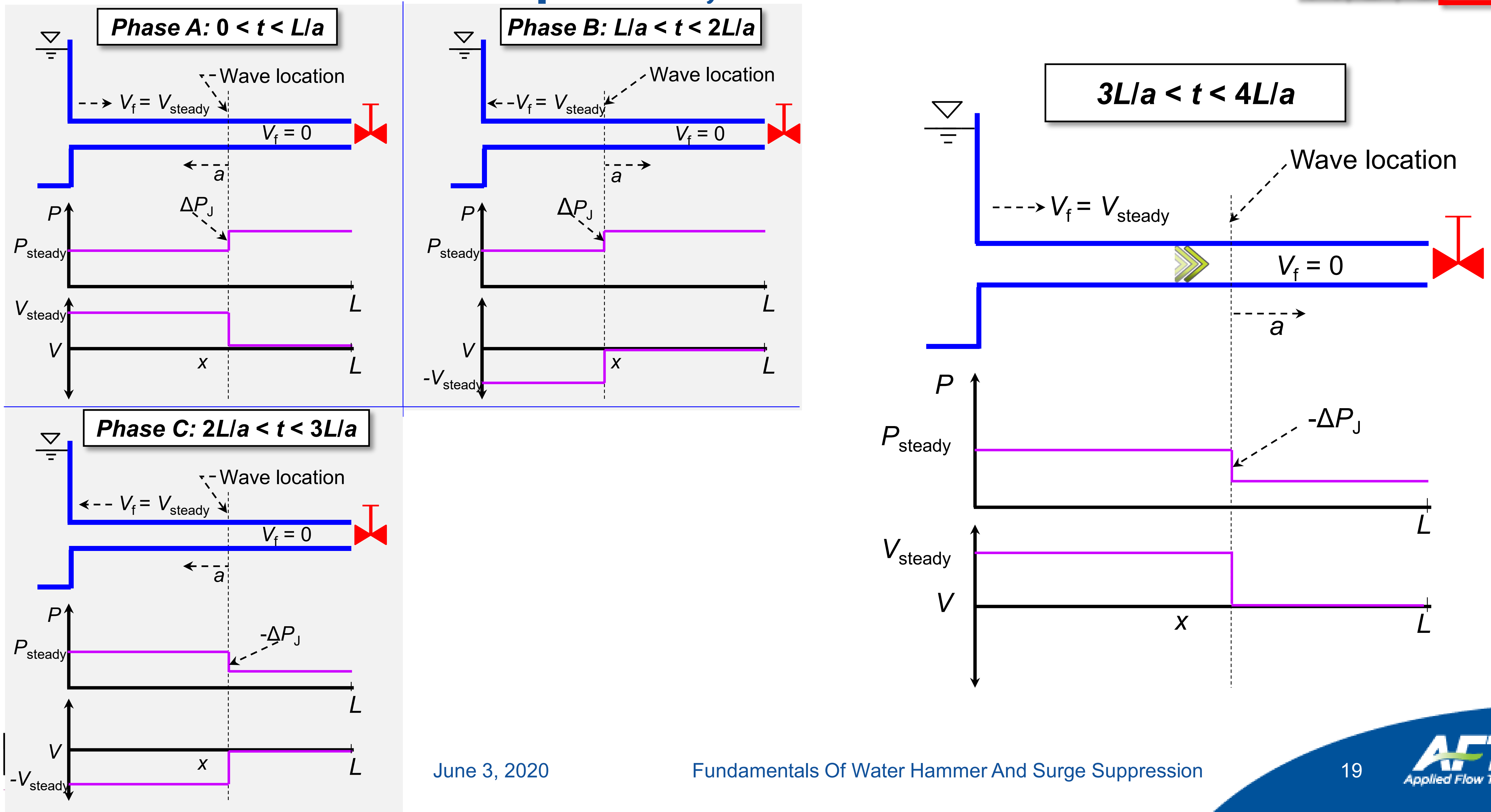

Applied Flow Technology

Fundamental Equations

- Mass / continuity equation

$$\rho a^2 \frac{\partial V}{\partial x} + \frac{\partial P}{\partial t} = 0$$

- Momentum equation

$$\frac{1}{\rho}\frac{\partial P}{\partial x} + \frac{\partial V}{\partial t} + g\sin(\alpha) + \frac{fV|V|}{2D} = 0$$

Where :

a = wavespeed
V = velocity
x = distance along pipe
P = pressure
t = time
g = gravitational constant
α = slope of pipe
f = friction factor
D = diameter of pipe

Solving the Fundamental Equations

- Most popular method is the Method of Characteristics
- *AFT Impulse* uses the MOC

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Technical Questions Answered by Waterhammer Analysis

1. Predict maximum pressures to avoid bursting the pipe
2. Predict minimum pressures to avoid large diameter pipes being crushed by vacuum conditions inside the pipe
3. Ensure proper operation of equipment such as maintaining adequate NPSH to operating pumps during the transient
4. Predict if the fluid reaches the vapor pressure and begins to cavitate – as discussed later this can generate even greater pressures after the cavities eventually collapse
5. Predict minimum pressures to avoid pulling a vacuum on the pipe and thus potentially contaminating a treated or a specialty fluid (e.g., treated water in a municipal distribution system) from outside ambient conditions
6. Size and locate surge suppression devices and systems to minimize high and low waterhammer pressures

Technical Questions Answered by Waterhammer Analysis (2)

7. Predict maximum or time varying imbalanced forces in the pipe system so pipe supports can be adequately designed
8. Ensure transient forces on components such as closed valves do not exceed the components' rated maximum value

Calculating Transient Forces for Pipe Stress Analysis

Wed Jun 17th 10:00am - 11:00am (MDT)

Generating unbalanced forces due to surge in AFT Impulse and exporting them to CAESAR-II.

Webinar

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Rotodynamic (Centrifugal) Pumps

- Pump transients cause and influence waterhammer
  - Trips
    - Planned
    - Unplanned
  - Startups
    - More complicated because transient motor/driver torque needs to be considered
- Types of responses depend on type of pump and presence of check valves
- With check valves, pumps do not generally experience backwards flows
- Without check valves, pumps can and do experience backwards flows and rotation
  - Why install pumps without check valves?
    - Fluid has solid particles (i.e., fluid is a slurry) that do not operate well with restrictions in the line
    - Pipe size is very large and check valve are not viable
    - Other

Rotodynamic Pumps With Check Valves: Zero or Minimal Backflow

- Pump behavior can be modeled with a simple torque balance equation and pump affinity laws

$$T_{shaft} = I_{total}\frac{d\omega}{dt} \qquad \int_0^{\Delta t}\left(T_{driver} - T_{pump}\right)dt = \int_{\omega_{old}}^{\omega_{new}} I_{total}\,d\omega$$

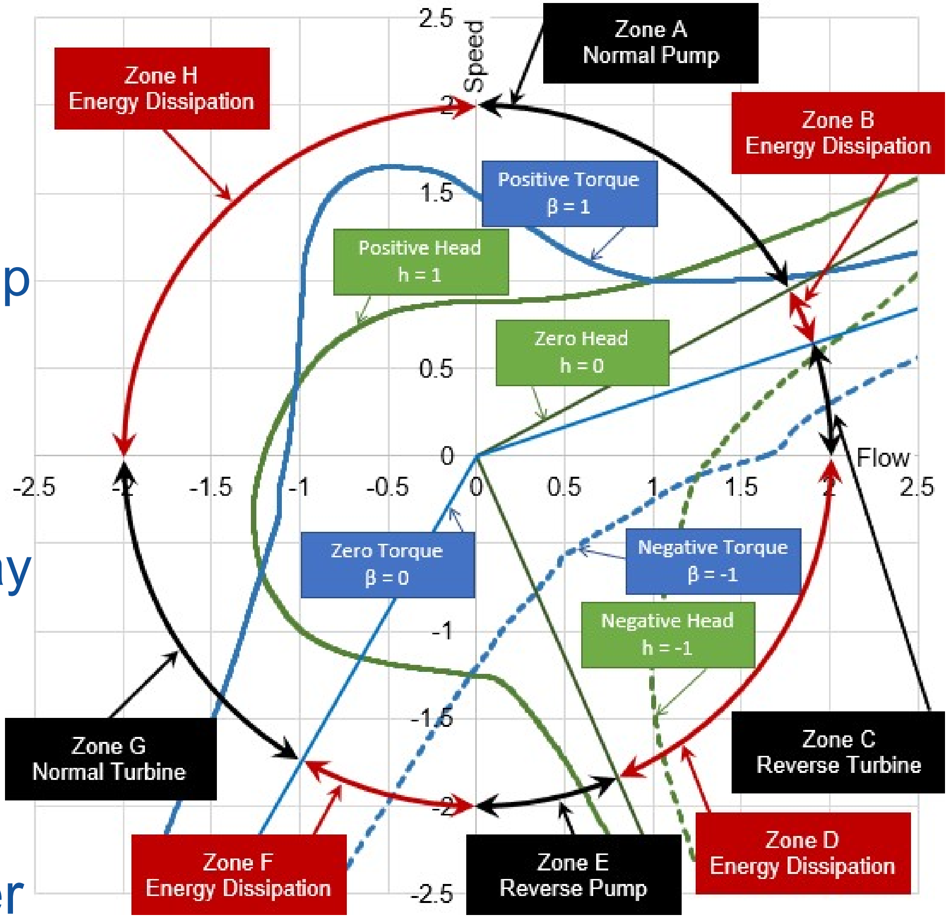
$$\frac{Q_1}{Q_2} = \frac{N_1}{N_2} \qquad Flow$$

$$\frac{\Delta H_1}{\Delta H_2} = \left(\frac{N_1}{N_2}\right)^2 \qquad Head$$

$$\frac{P_1}{P_2} = \left(\frac{N_1}{N_2}\right)^3 \qquad Power$$

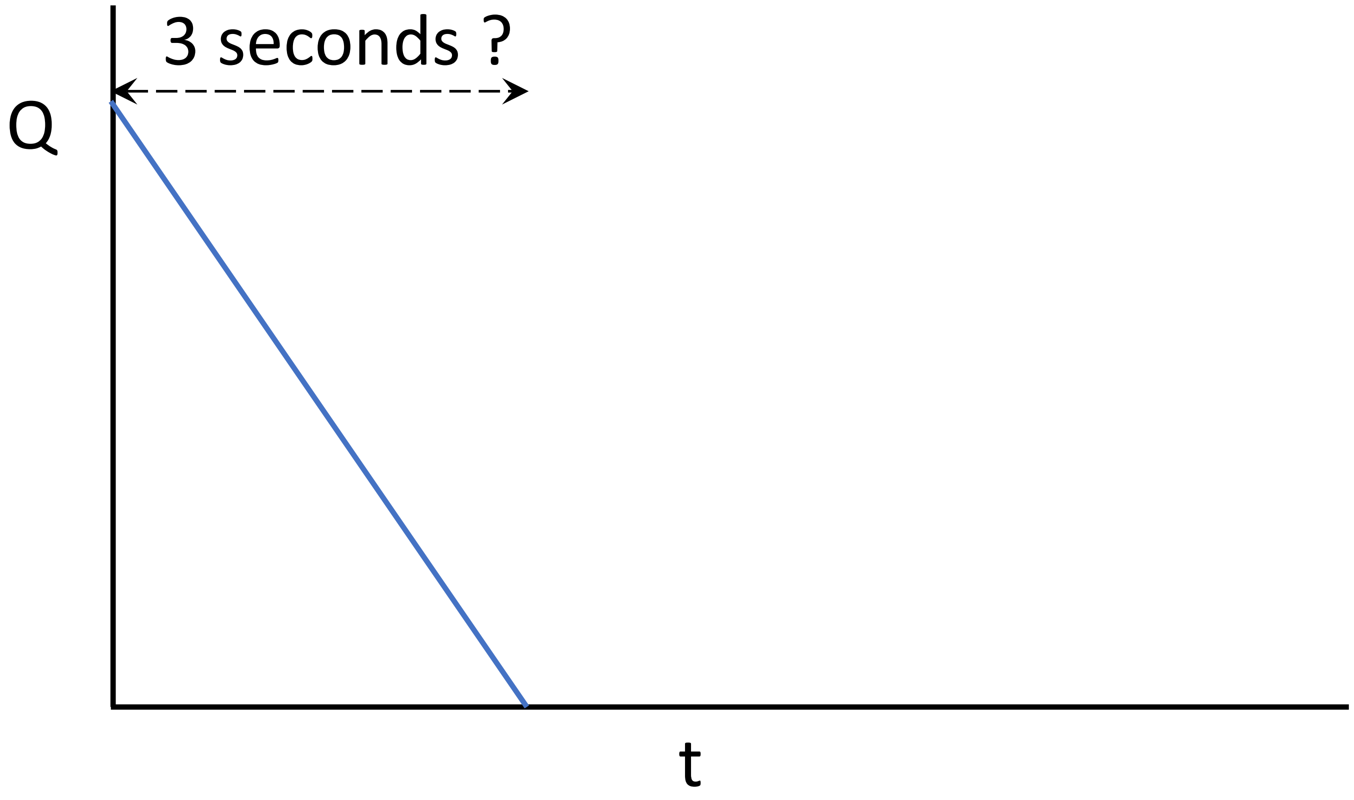
Rotodynamic Pumps Without Check Valves: Operation in All Four Quadrants

- Pump behavior must be estimated in all four quadrants from previous measurements
  - Unless the engineer is able to get data for their pump
- This data is this called "four quadrant data"
  - Commonly pumps with similar specific speed are used
  - Recent research suggests engineers should also pay attention to
    - initial and final steady-state conditions
    - shape of pump curves between their pump and the previously published pumps in the first quadrant
- Calculations are typically performed using the Suter Method



Positive Displacement Pumps and Waterhammer

- Typical assumption in modeling is that the flowrate decays quickly (in a few seconds)



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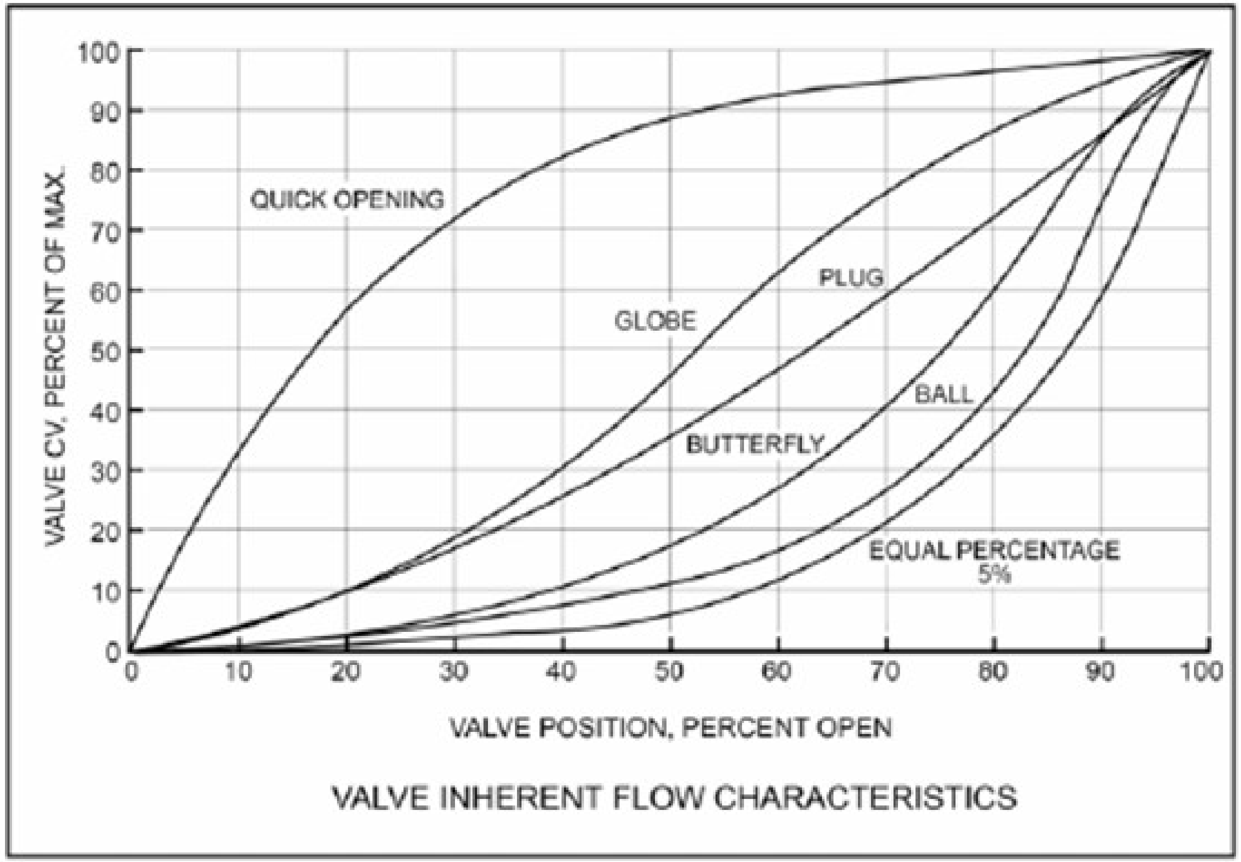
Valve Cv Profiles

- Waterhammer pressure responses are sensitive to the shape of the Cv profiles
- Also sensitive to the rate of actuation
  - Linear
  - Non-linear



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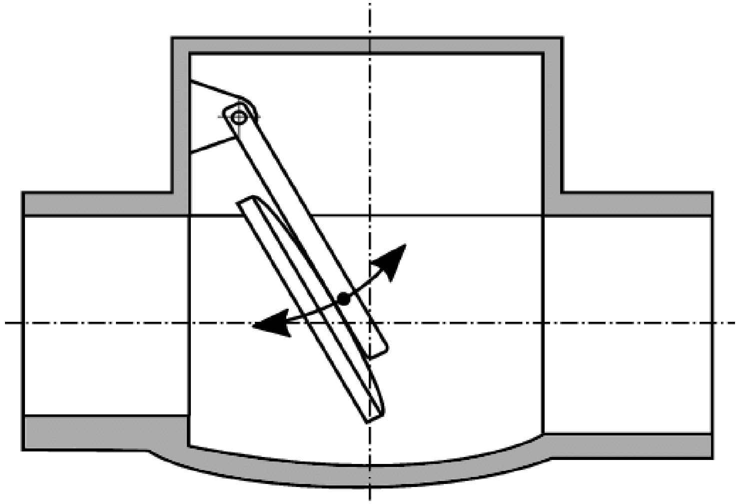
Check Valve Designs

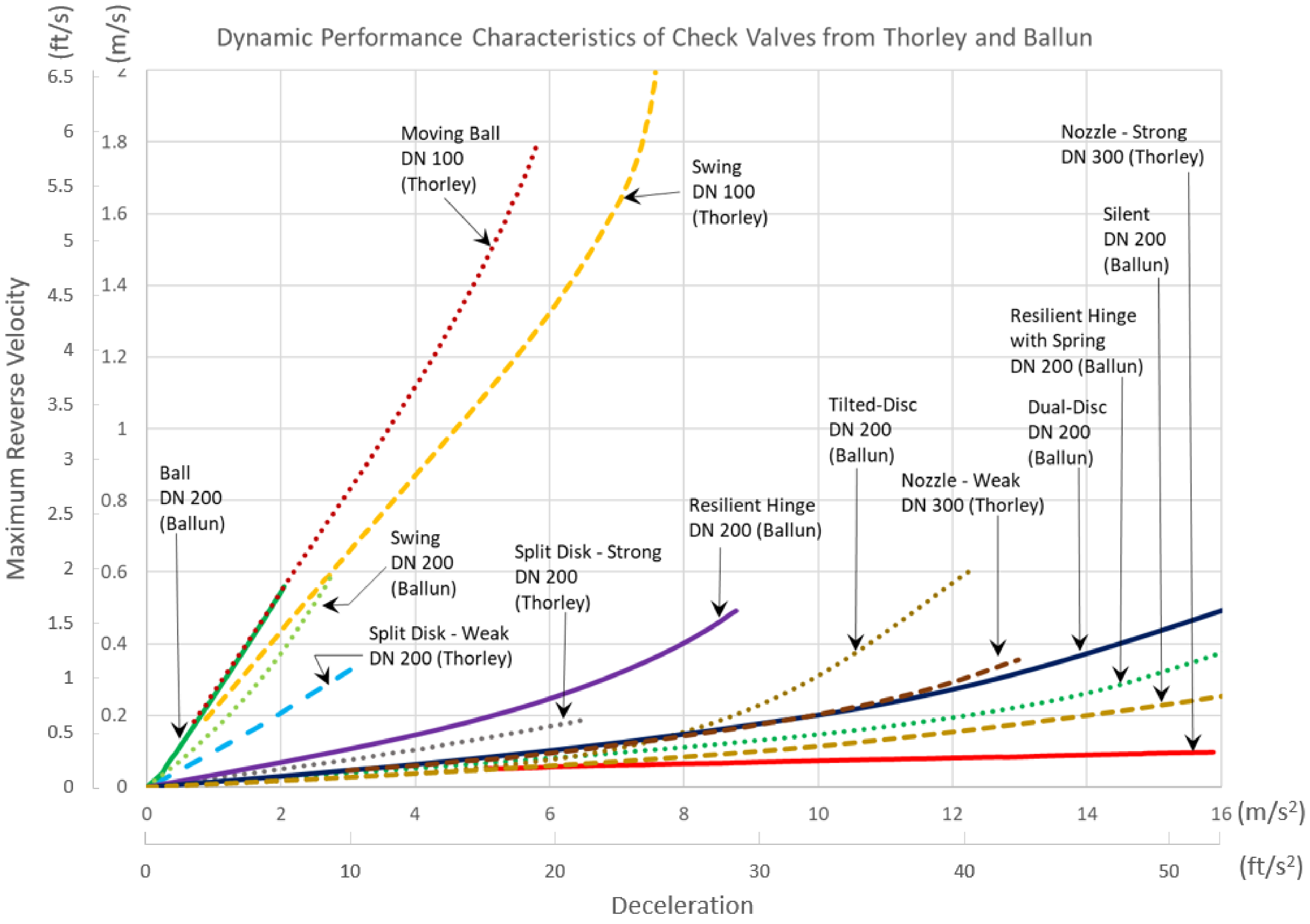
- When the flow reverses through a check valve, it will slam closed
- Check valves have different designs which lead to different responses to reverse flow
- Here are two common types:

Swing Check Valve



Nozzle Check Valve

Check Valve Performance Characteristics



BLACOH™ SURGE CONTROL

AFT Applied Flow Technology

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Transient Cavitation

- Transient cavitation is also called liquid column separation
- The presence of vapor slows down wave speed propagation
  - This is generally neglected in analyses because:
    - It is very difficult to predict wave speed changes with liquid and vapor
    - It is typically conservative for peak pressures to assume higher, 100% liquid wavespeeds
- Transient cavitation is very difficult to predict
  - The best models are not especially good
  - The two most popular models:
    - DVCM – Discrete Vapor Cavity Model
    - DGCM – Discrete Gas Cavity Model
      - » The DGCM model has an uncanny ability to mimic wavespeed decreases due to vapor presence

Transient Cavitation (2)

- It is good practice to avoid the possibility of transient cavitation if possible because it is so hard to predict
- If one must allow transient cavitation, then larger safety factors are recommended
  - See "Stewart, Walters, Wunderlich and Onat (2018)"

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Surge Can Be Reduced By Using Different Pipe Materials

- Different materials affect the wavespeed, which affects the pressure surge magnitude

$$\Delta P = -\rho a \Delta V$$

Pipe Material	Wavespeed in 4 inch Pipe	
	ft/s	m/s
Carbon Steel	4350	1325
Copper	4150	1250
FRP	2650	800
Green Thread Fiberglass	2150	650
HDPE	900	275

Surge Can Be Reduced By Changing Component Behavior

- Use different valve:
  - Types
  - Closure times
  - Closure profiles
  - Arrangement - add parallel valves to stagger closure
- Add inertia to pumps
  - Flywheel

Surge Can Be Reduced By Adding Surge Relief Valves

- For protection against high pressures
- Often special fast-opening, slow closing
- If surge valve closes too quickly can cause secondary surge events
- May require relief piping

Surge Can Be Reduced By Adding Vacuum Breaker Valves

- For protection against low pressures
- Typically used only for water systems
- Often large flow area coming in and small flow area going out
- Often located at high points in the system for pipelines
- Often located around condenser inlet and outlet in condenser cooling water systems

Vacuum breaker valves (in green, at left) at pump discharges

Surge Can Be Reduced By Adding Surge Vessels

- Open atmospheric vessels
- Closed pressurized vessels
- Protection for both high and low pressures
- Informative YouTube video
  - https://youtu.be/fy072vKK_8I

Closed surge vessel at a reused water pump station

Surge Can Be Reduced By Adding Surge Vessels

Surge Can Be Reduced By Adding Surge Vessels (2)

Surge Can Be Reduced By Adding Surge Vessels (3)

Surge Can Be Reduced By Adding Surge Vessels (4)

Surge Can Be Reduced By Adding Surge Relief Piping

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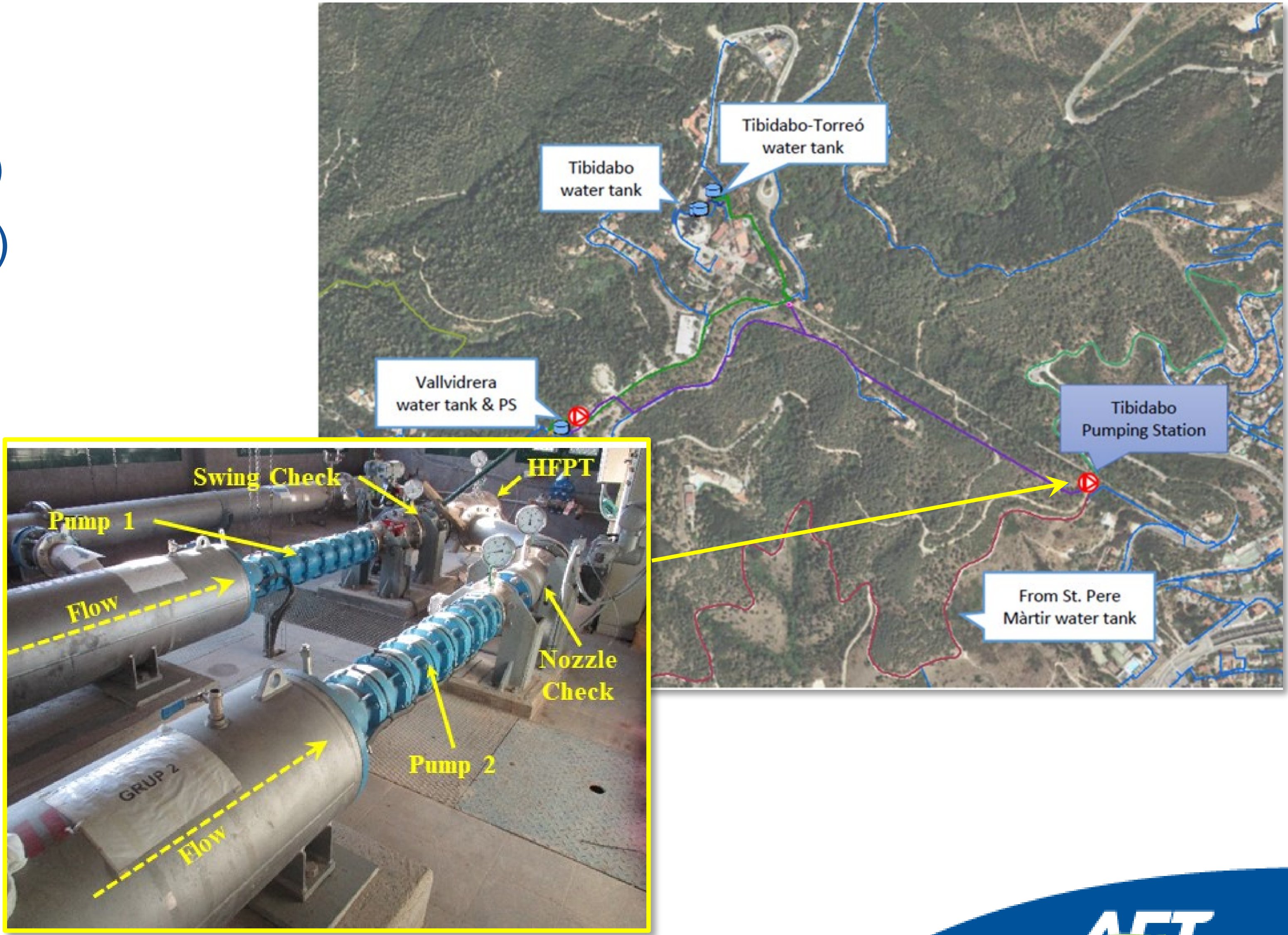
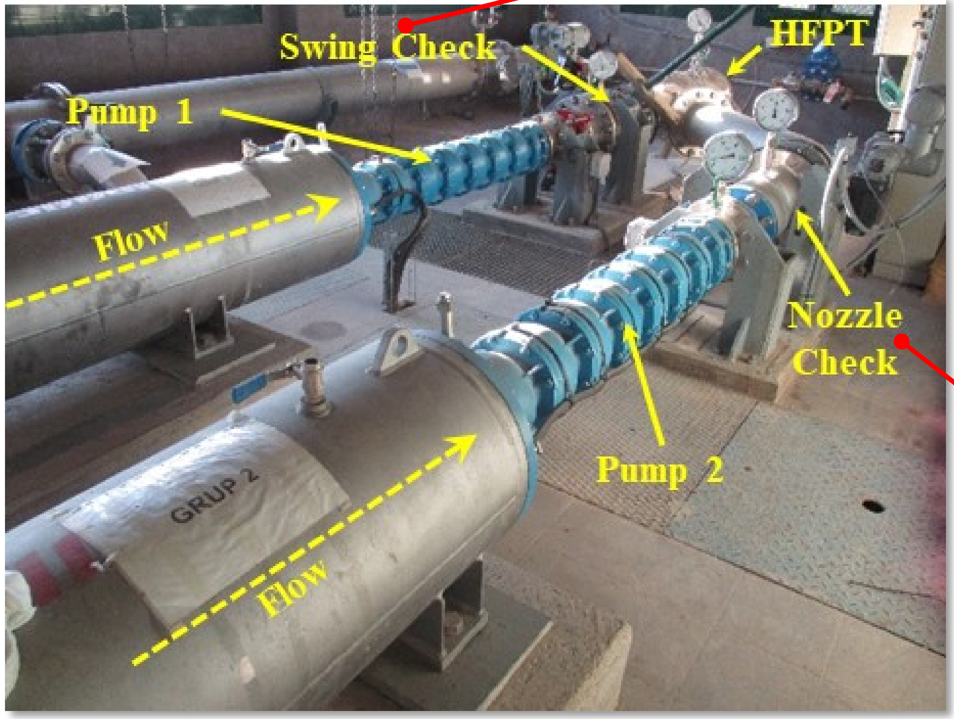
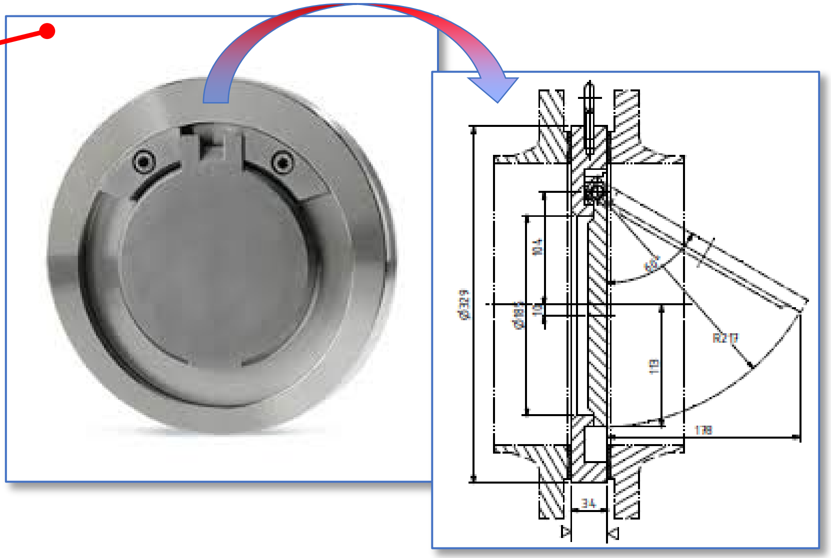
Check Valve Slam in Municipal Water Pump Station Barcelona, Spain

- Diameter = 12 inches (30 mm)
- Material = Ductile Iron (mostly)
- Pipe Length = 0.8 mi (1.3 km)
- Elevation rise = 450 ft (137 m)
- Axial flow pumps
  - One operating, one standby
  - Surge tanks on suction and discharge



Check Valve Details

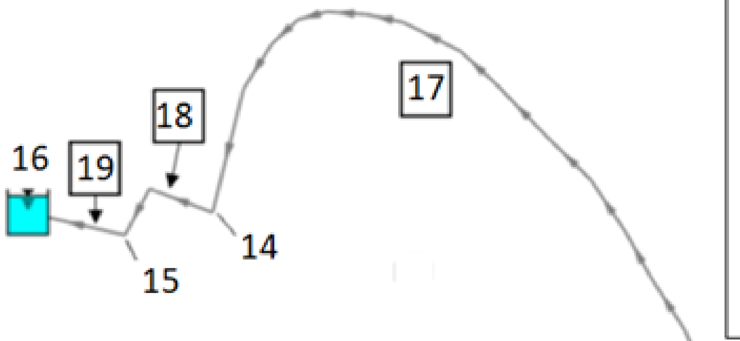




Swing Check Valve

Nozzle Check Valve

AFT Impulse Model



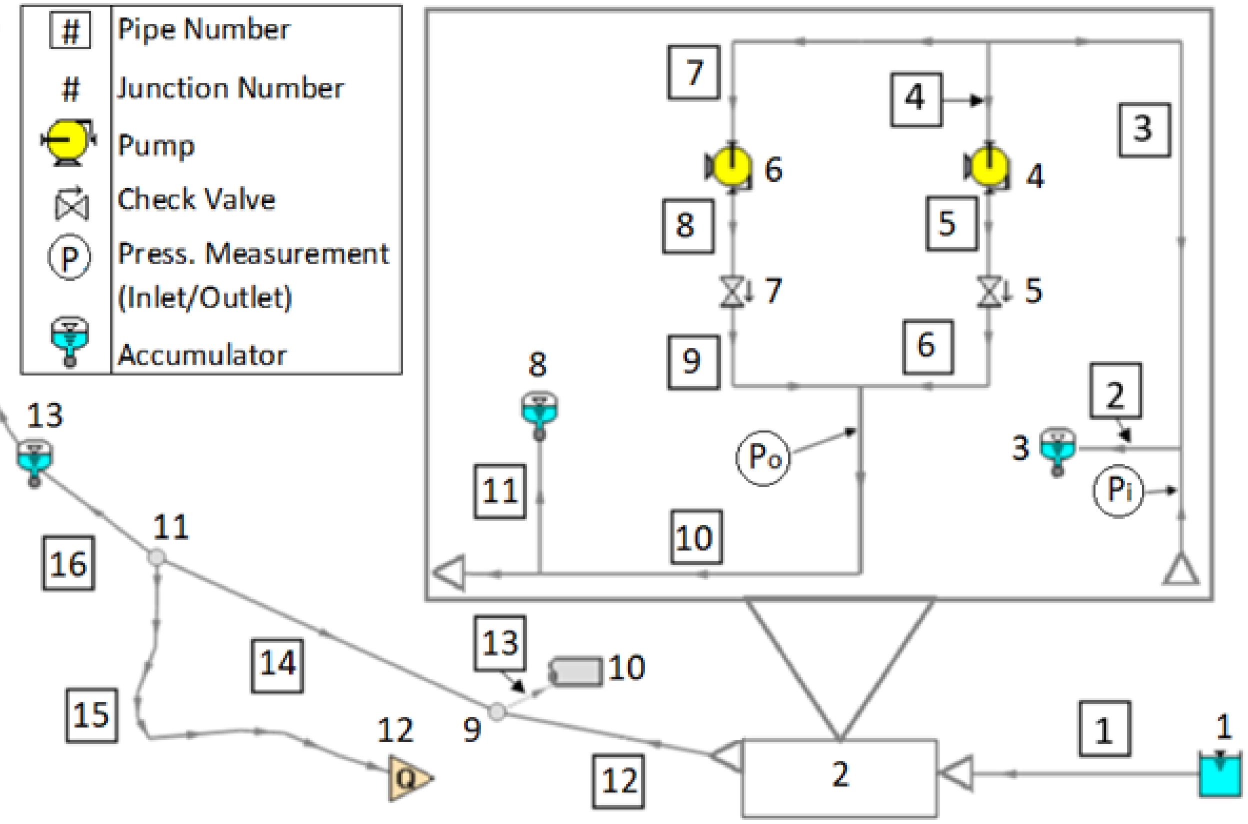


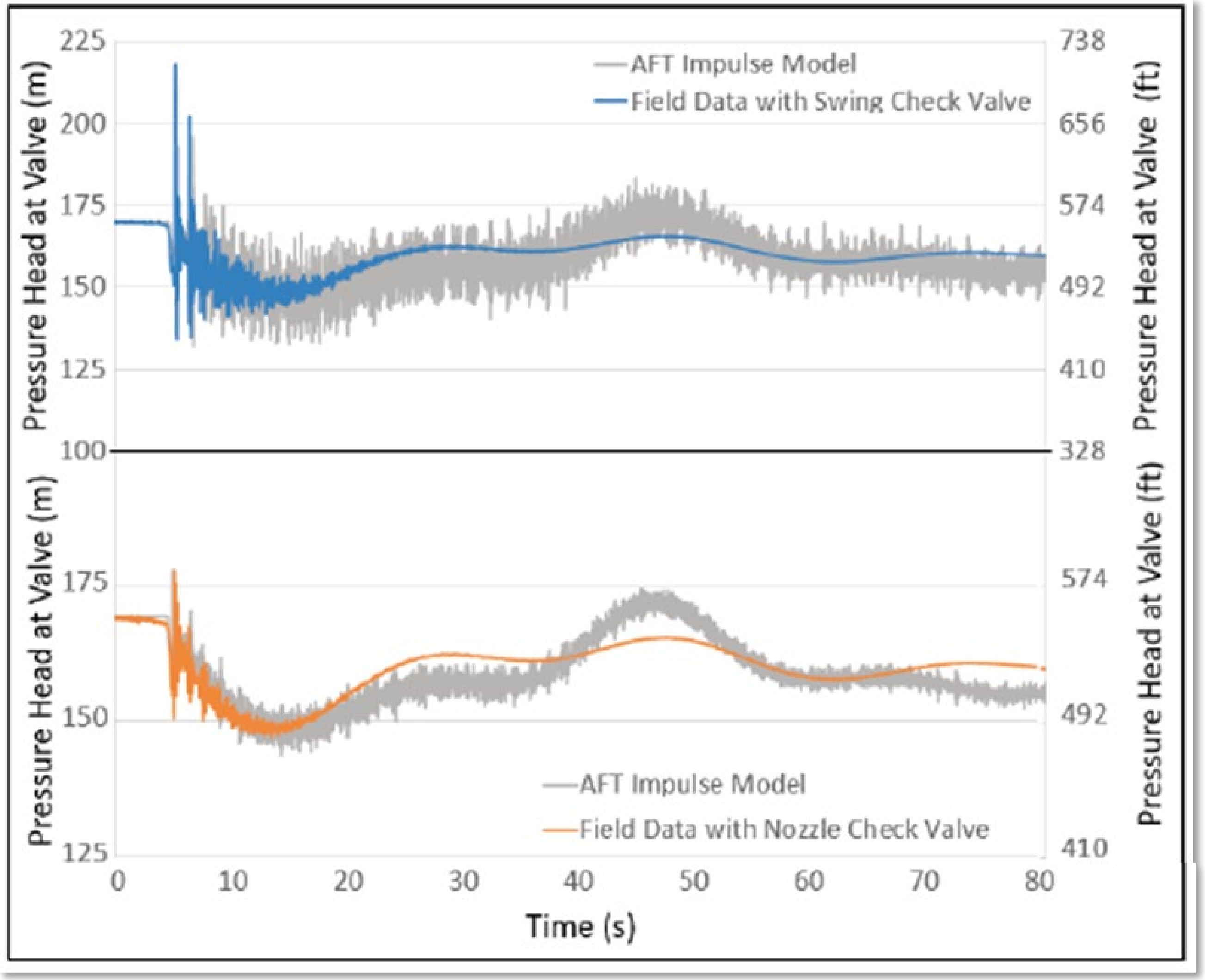
Diagram Elevations

Label	Object	Elevation (m)
1	Sant Pere Martir	302,6
2	Tibidabo Pumping Station	280
9	Branch to house	305,64
10	Abandoned House	300,35
11	Branch to Fabra	418,09
12	Fabra Observatory	410,28
13	Link to Tibidabo Torreo	430,96
14	Intermediate elevation	429,39
15	Intermediate elevation	440,69
16	Valvidrera	440,73

AFT Impulse Model Predictions vs. Field Data

Swing Check Valve

Nozzle Check Valve



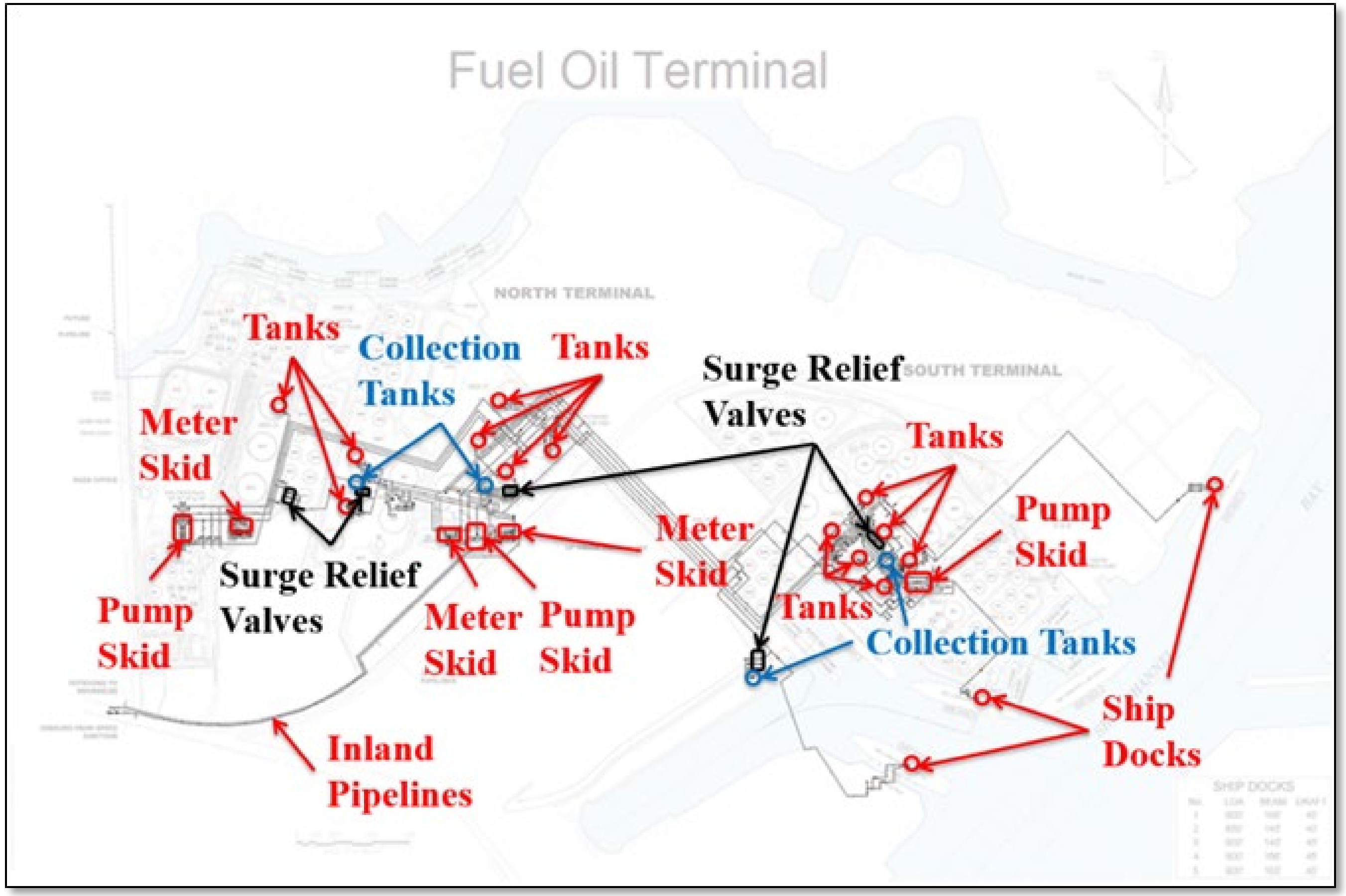
Check Valve Slam in Municipal Water Pump Station Conclusions

- Nozzle check valves significantly reduce pressure surge from check valve slam
- *AFT Impulse* simulation tool are able to predict fairly well surge transients in Barcelona’s water system
- Presented at Pressure Surges 2018 conference in Bordeaux, France, November 2018, "Surge transients due to check valve closure in a municipal water pumping station"

Surge Mitigation in a Marine Fuel Oil Terminal: U.S. Gulf Coast

Gulf Coast marine fuel oil terminal

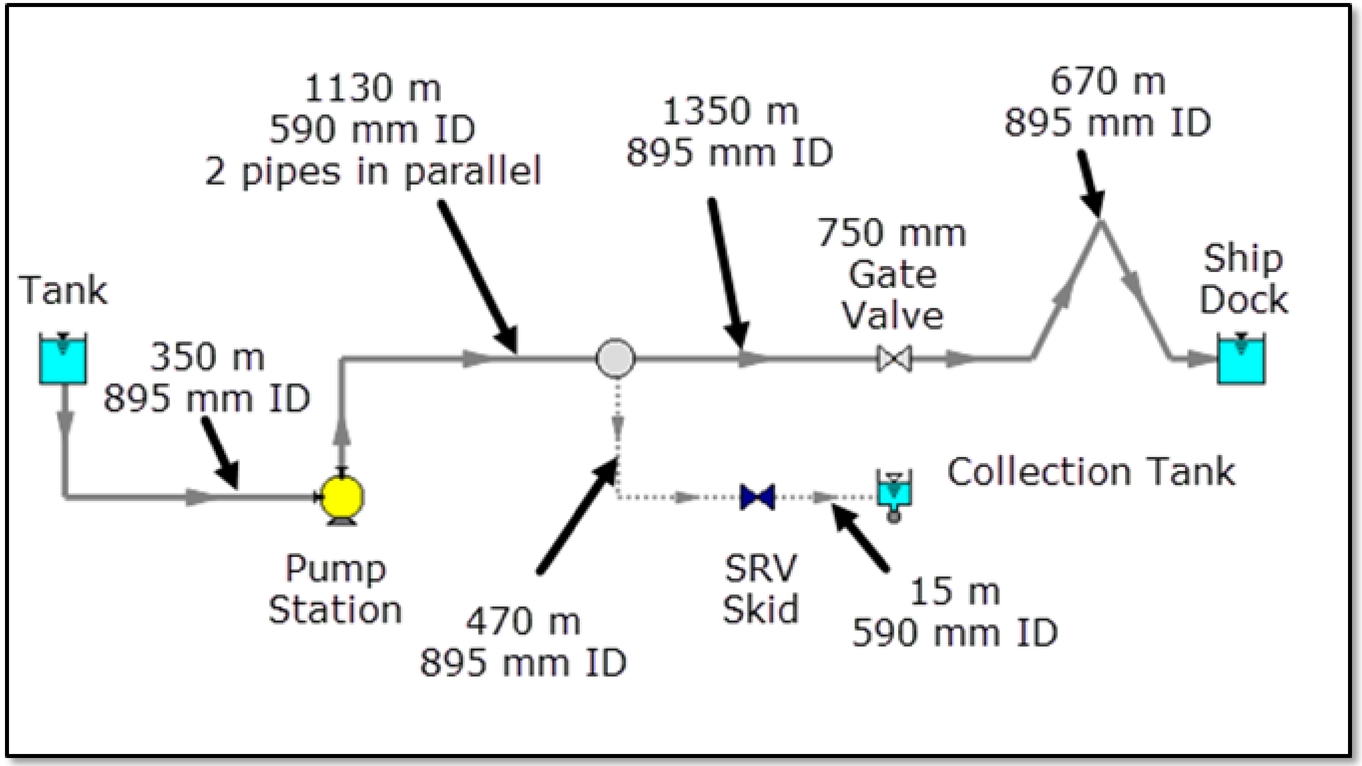
- Over 40 mi (65 km) of network piping modelled
- Inbound and Outbound flows
- Hundreds of operating cases modeled
- Various combinations of mitigation methods
  - Nitrogen backed surge relief valves
  - Dual rate valve stroking



Marine Fuel Oil Terminal *AFT Impulse* Model

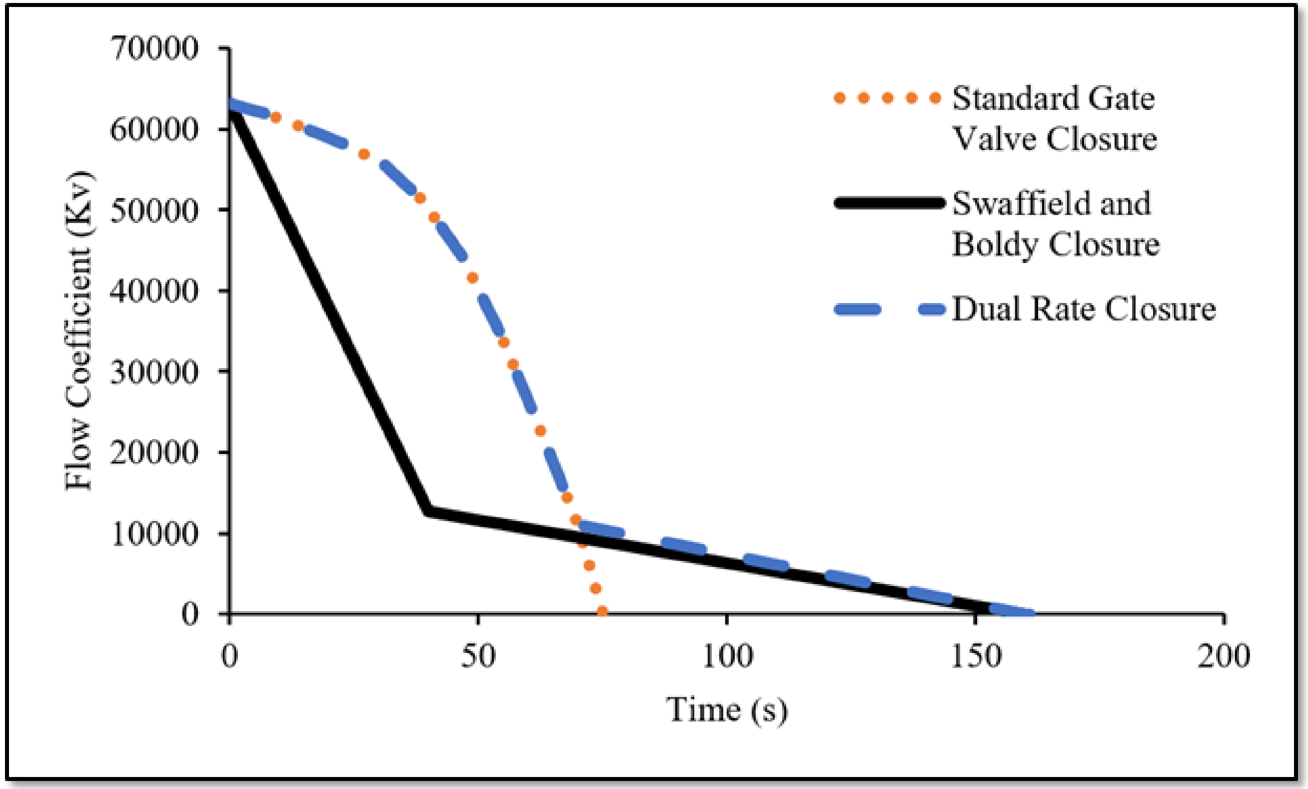
- Flow length: ~3750 m (2.3 mi)
- Wavespeed: ~1100 m/s (3600 ft/s)
- Pipeline period: ~7 s
- Initial flow: 1.312 m3/s (20,000 gpm, 30,000 bph)
- Fluid: Crude Oil
  - SG: 0.93
  - 54 cP

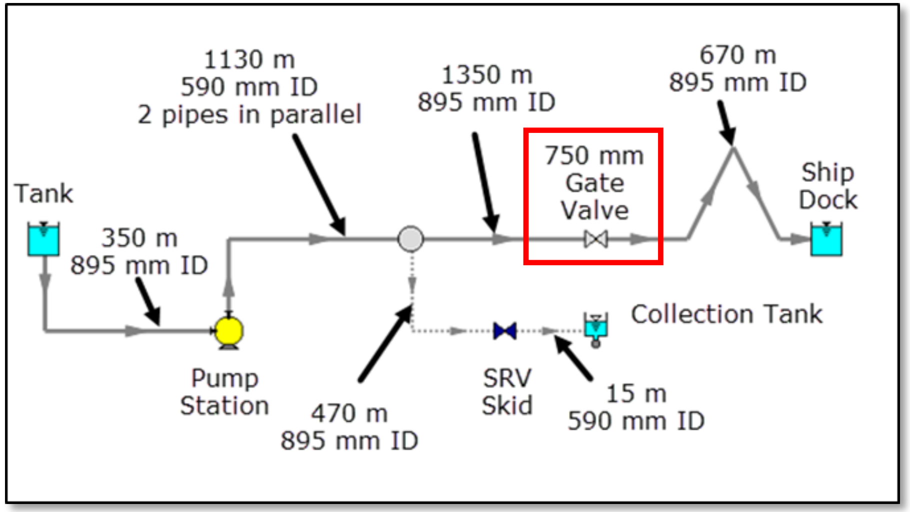
Simplified model view of flow path and relief line



Marine Fuel Oil Terminal: Valve Closure

- Linear actuated gate valve closure has a poor closure profile
- Considered a hybrid closure using a standard closure and a Swaffield and Boldy Closure



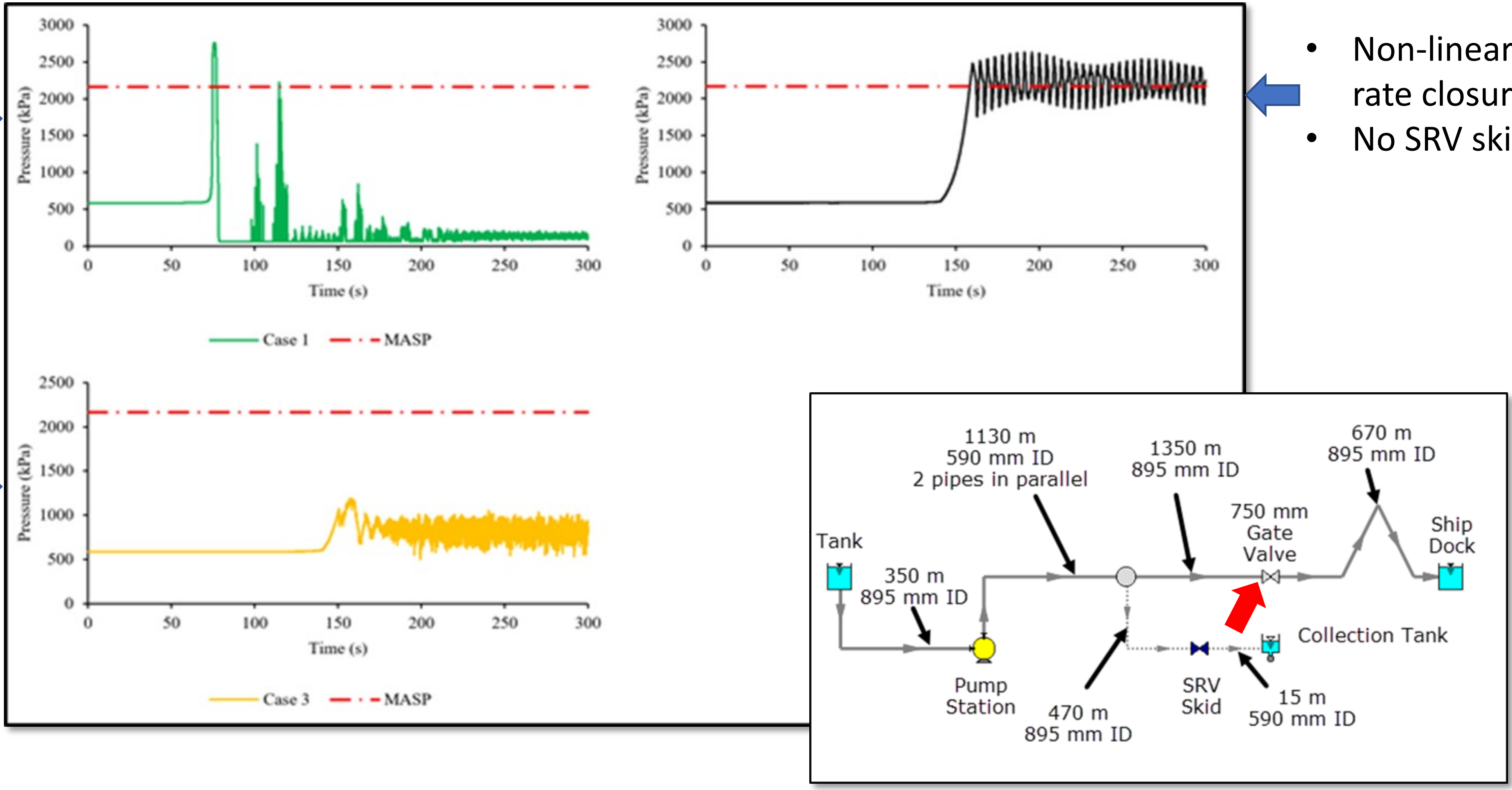


Marine Fuel Oil Terminal: Simulation Results at Gate Valve

- Linear valve closure
- With SRV skid

- Non-linear dual rate closure
- No SRV skid

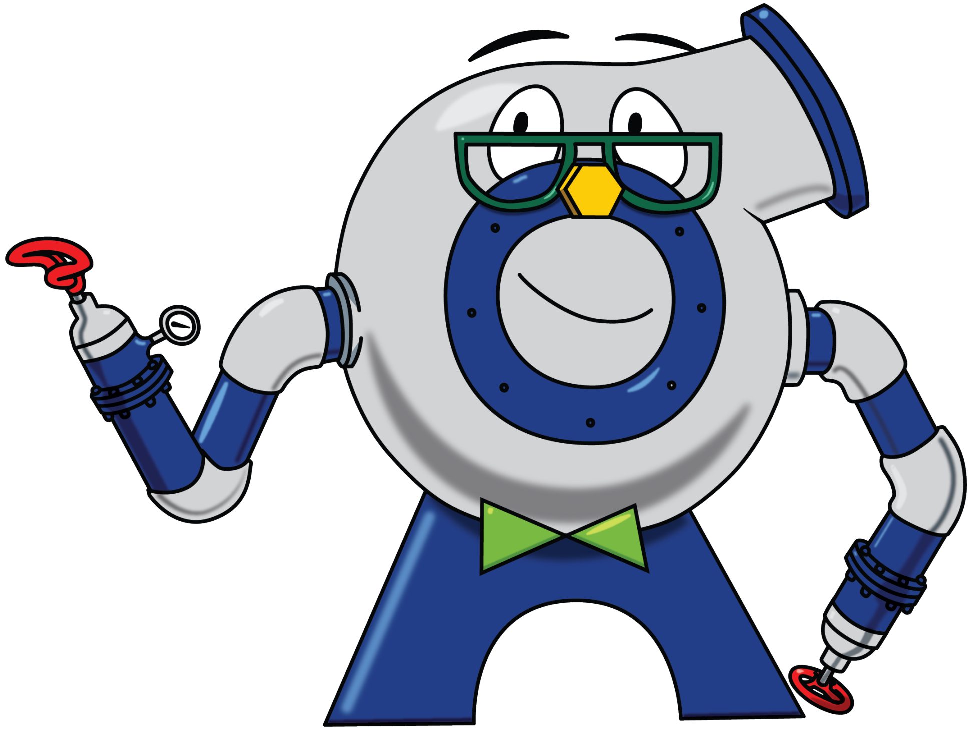
- Non-linear dual rate closure
- With SRV skid



Surge Mitigation in a Marine Fuel Oil Terminal Conclusions

- Various surge mitigation methods can be used together to create a cost effective solution
- Care must be taken when introducing a secondary flow path to relieve pressure
  - Rapid closures on this flow path still result in pressure rise and can be worse than the original valve closure
- Using dual rate valve actuation can significantly reduce peak surge pressures and in some cases can eliminate the need for relief systems
- Presented at Pressure Surges 2018 conference in Bordeaux, France, November 2018, "Surge Mitigation in a Marine Fuel Oil Terminal"

Questions?



Professor Pumphead

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Waterhammer YouTube Videos

- Videos of piping system waterhammer
  - http://www.youtube.com/watch?v=oZbguheiVs4&NR=1
  - http://www.youtube.com/watch?v=U0XfYCKxZks
- CFD simulation of the water hammer
  - http://www.youtube.com/watch?v=ng__hdZ8yD8
- High speed movie of a cavitating valve
  - http://www.youtube.com/watch?v=X9UbzcanuDk
- Video of column separation in a clear line
  - http://www.youtube.com/watch?v=bmcOpuzemRU

Waterhammer YouTube Videos (2)

- Pump trip and column separation
  - http://www.youtube.com/watch?v=E6NIA4LxPPw
- Pressure surge with and without an accumulator
  - https://www.youtube.com/watch?v=BxNq37VmYk8&index=49&list=PLc7cKQUNMoJojqJdsiWgURvHBNp_cCFtd
- Gas bladder accumulator close to pump after pump trip
  - http://www.youtube.com/watch?v=kiTzez0x6aQ
- Surge behavior, simulation and monitoring
  - https://www.youtube.com/watch?v=fy072vKK_8I&feature=youtu.be