



# ***Physics*** **Of Centrifugal Pumps & Cavitation Case Histories**

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**Presented By:**

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# **Are Pumps Important?**

**PUMPS  
Are Critical  
to our life on this Planet?**

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**How Long Would The World  
We Know Continue If  
All Pumps Stopped Working?**

**PUMPS ARE  
CRITICAL**

# Introduction

## Radial Flow Centrifugal Pumps

- ❖ **Centrifugal Pumps are simple machines. A centrifugal pump moves a liquid against gravity, pressure forces and system friction. They use centrifugal force generated by a rotating impeller/shaft to move a liquid.**
- ❖ **The shaft/impeller accelerates (throws) the fluid outward toward the tip of the blades at the periphery of the impeller. At this point the fluid is discharged at a higher velocity than at the impeller inlet. The higher the velocity, the higher the feet of head the pump can generate. This process requires energy (Pump Water Horsepower).**

## Pumps Require Energy

$$\text{❖ Pump Water HP} = \frac{\text{GPM} \times 8.33 \times \text{Total Head}}{33,000}$$

$$\text{❖ Pump Water HP} = \frac{\text{GPM} \times \text{Total Head}}{3960}$$

$$\text{❖ Pump Motor HP} = \frac{\text{GPM} \times \text{Total Head}}{3960 \times \text{Motor/Pump Eff. (70\%-75\%)}}$$

$$\text{❖ Motor Amps (3-Phase)} = \frac{\text{BHP} \times 1.732}{\text{Voltage} \times \% \text{ Motor Eff.}}$$

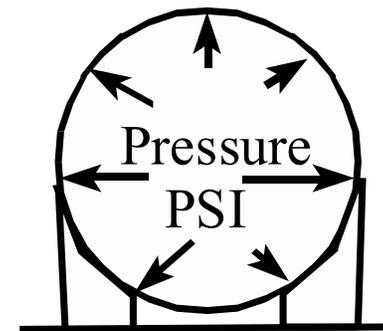
$$\text{❖ Single Phase} = \frac{\text{BHP} \times 746}{\text{Voltage} \times \% \text{ Motor Eff.}}$$

- ❖ **Centrifugal Pumps Convert Mechanical Energy (Shaft Torque ) Into Kinetic Energy (Acceleration/Velocity) and Potential Energy (Pressure (psi) using centrifugal force.**

$$\text{Shaft Torque (Ft. Pounds)} = \frac{\text{Motor BHP} \times 5350}{\text{RPM}}$$

- ❖ **The fluid's velocity reduces as it exits the impeller and enters the pump casing (volute). A portion of the Kinetic Energy (velocity) of the moving fluid is transformed into pressure(psi). Pressure is a force that tries to burst the pipe, tank or pump housing.**

- ❖ **(1 psi = 2.31 feet of head)**



- ❖ **Available Head (Theoretical head) that a centrifugal pump impeller can develop at a given operating speed can be calculated using the law of falling bodies.**

$$\text{Available Head (H)} = \frac{V^2}{2g}$$

**H = height of fluid (lift) or head in feet that can be developed by the velocity of a fluid as it exits the pump impeller.**

**V = velocity of the moving fluid in fps leaving the tip of the impeller vanes.**

**g = acceleration of gravity (32.2ft/sec<sup>2</sup>)**

# PUMP IMPELLER CALCULATIONS

$$\text{Impeller Dia. (inches)} = \frac{\left( \sqrt{H \times 2g} \right) 229.2}{\text{RPM of the impeller}}$$

**Example:**

**H = 100 ft head**

**2g = 64.4 ft/sec<sup>2</sup>**

**1800 RPM Impeller**

$$\frac{\left( \sqrt{100 \cdot 64.4} \right) \cdot 229.2}{1800} = 10.22 \text{ in diam.}$$

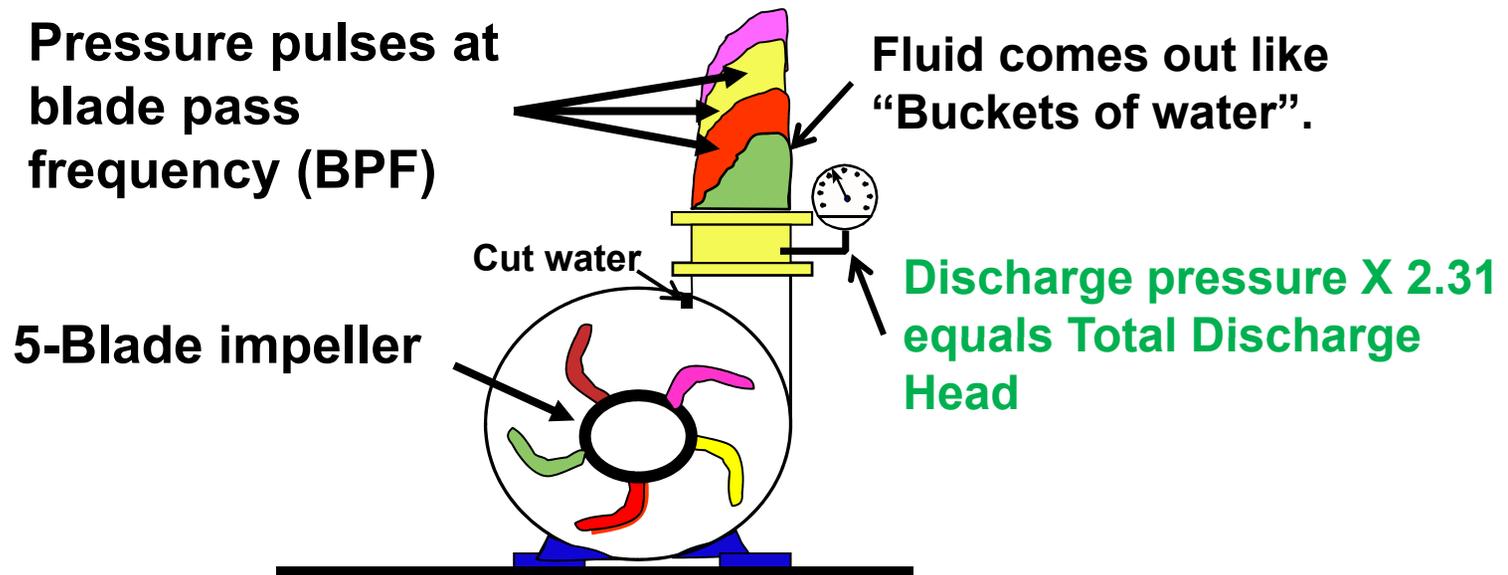
## Shortcut Technical Tip:

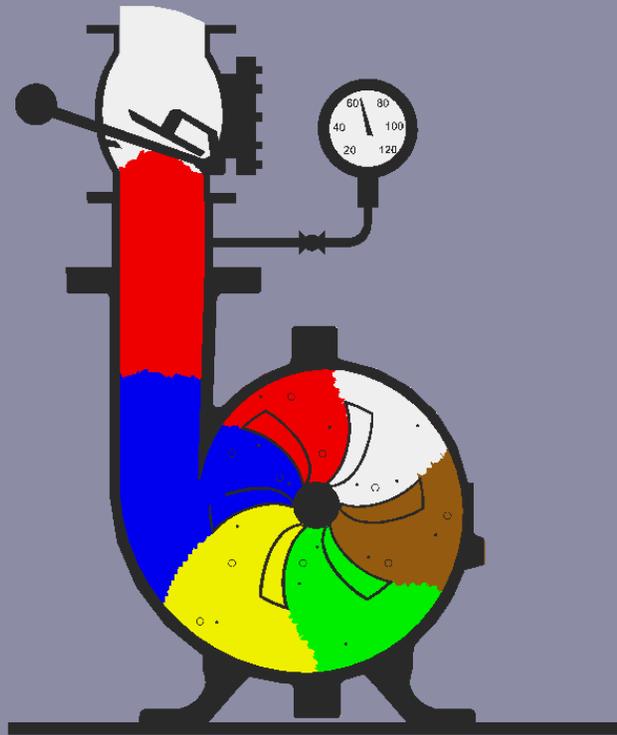
**Pumps operating at 1800 RPM will develop a theoretical head (Total) approximately equal to the impeller diameter (inches) squared.**

**Example:**

**A pump with an impeller 12" in Dia. @ 1800 RPM will develop 144 ft of Total Head**

- ❖ Rotation of the pump's impeller accelerates the fluid as it passes through the impeller. This acceleration produces the velocity and pressure required to develop a certain head in feet (doing the work). Like the old time bucket brigade fighting a fire. Each impeller section (between the vanes) throws out a "bucket" of water.





BLADE PASS WITH CK VLV.avi

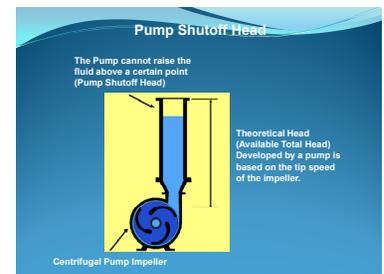
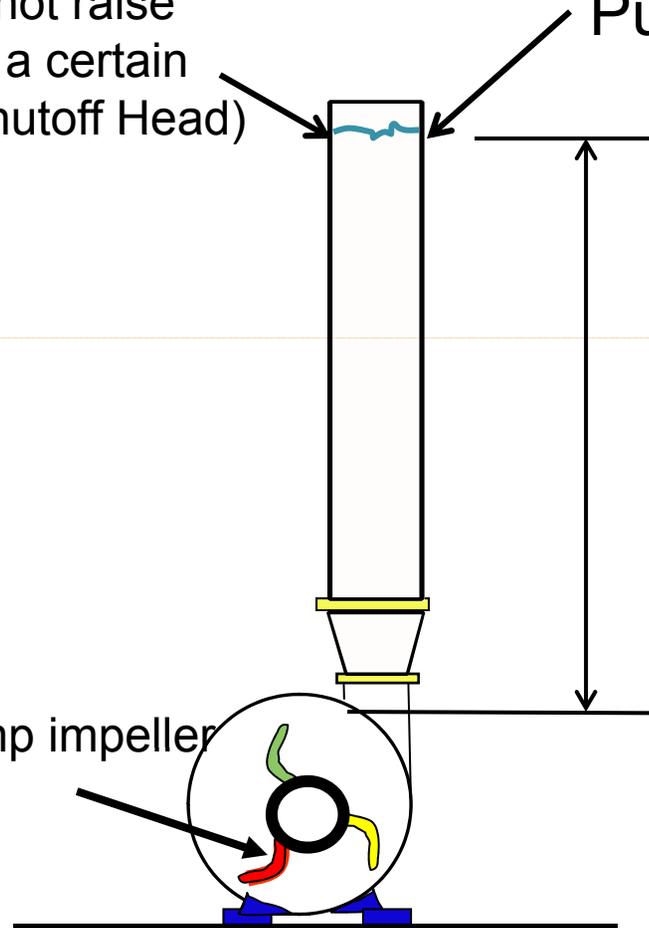
# PUMP SHUTOFF HEAD

The Pump cannot raise the fluid above a certain point (Pump Shutoff Head)

Pump Shutoff Head

Theoretical Head (Available Total Head) developed by a pump is based on the tip speed of the impeller.

Centrifugal Pump impeller



# Centrifugal Pump And Piping Vibration

## WHAT IS VIBRATION?

### Vibration:

Webster's New World Dictionary defines Vibration as "to swing back and forth; to oscillate"

Vibration (Forced) is caused by a Forcing Function or pulsating motion of a machine part or rotating component (Pump Impeller or fluid flow) that causes the machine or piping to move/oscillate from it's original place of rest.

### Forcing Frequency:

The frequency at which a machine is forced to vibrate by a Forcing Function or functions.

## **Vibration Amplitude:**

**The magnitude or size of the vibration movement (Displacement) indicating severity.**

Standard Units – Displacement

**Vibration Amplitude is proportional to**  $\sim \frac{\text{Dynamic Force}}{\text{Dynamic Resistance}}$

## **Dynamic Force:**

**A physical force or energy that causes acceleration.**

## **Dynamic Resistance**

**An opposing or retarding force that resists movement generated by a dynamic force such as mass/stiffness or arrangement.**

## Terms:

### Velocity (V):

The amount of fluid flowing past a point in a given time. Flow velocity in a pipe:  $V = \frac{.4085 \text{ gpm}}{d^2}$   
d = inside diameter of pipe

### Velocity Head ( $h_v$ ):

The vertical distance a body has to fall to reach the velocity V. This is the static head or pressure needed to cause a given velocity.

$$h_v = \frac{V^2}{2g} \quad h_v = \frac{.00259 \text{ (gpm)}^2}{d^4}$$

### Total Static Head ( $h_{ts}$ ):

The vertical distance between the open end of the discharge and the inlet (suction) line.

## **Terms:**

### **Friction Head ( $h_f$ ):**

**The resistance to flow in a system (piping) measured in terms of ft of liquid (Head).**

### **Net Positive Suction head Available (NPSHa):**

**The available head in ft available at the suction inlet of the pump.**

### **Net Positive Suction Head Required (NPSHr):**

**The pump manufacturer will supply this with the pump curve.**

**Total Discharge (Dynamic) Head (TDH):**

**The pressure reading at the pump discharge converted to head (PSI x 2.31) plus the velocity head at the point where the gauge is attached.**

**Total Head (H):**

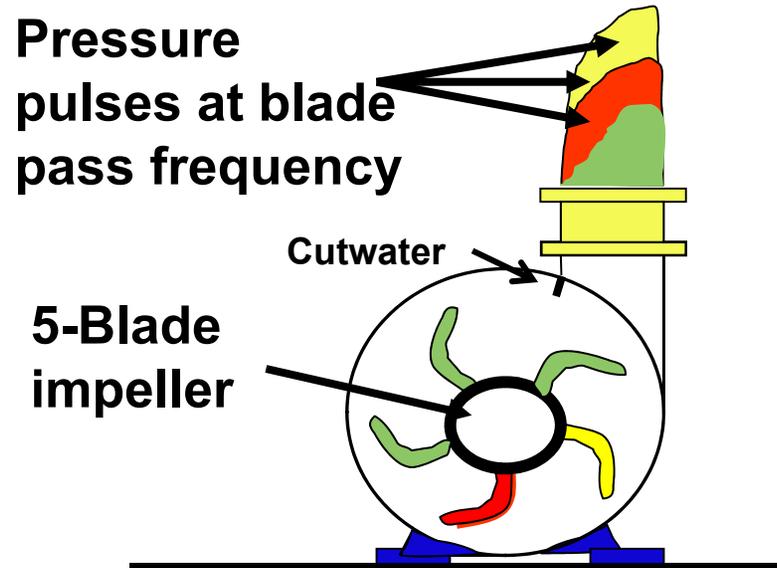
**Total Discharge Head minus the total suction head**

**Cavitation:**

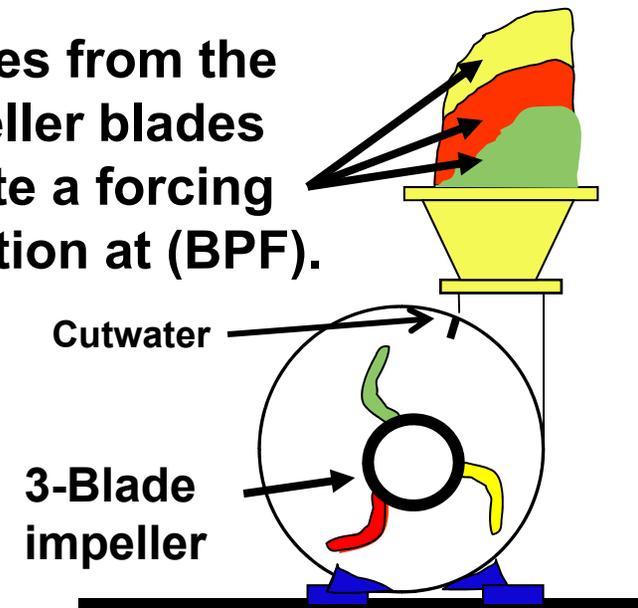
**Webster's New World Dictionary defines Cavitation as "the creation of partial vacuums in a liquid caused by a high speed solid object (impeller). The pitting & wearing away of solid objects by the collapse of the vacuums (bubbles) in the surrounding liquid".**

# Forcing Functions Generated By Pumps (Dynamic Forces)

“Forcing Functions” are created by the action of machine components such as Pump Blade Pass Frequency (BPF) occurring at a repetitive rate or periodic rate. This is usually expressed in (Hz) or cycles per minute (CPM), or multiples of running speed. The energy (Dynamic Force) contained per pressure pulse is inversely proportional to the number of pump impeller blades.

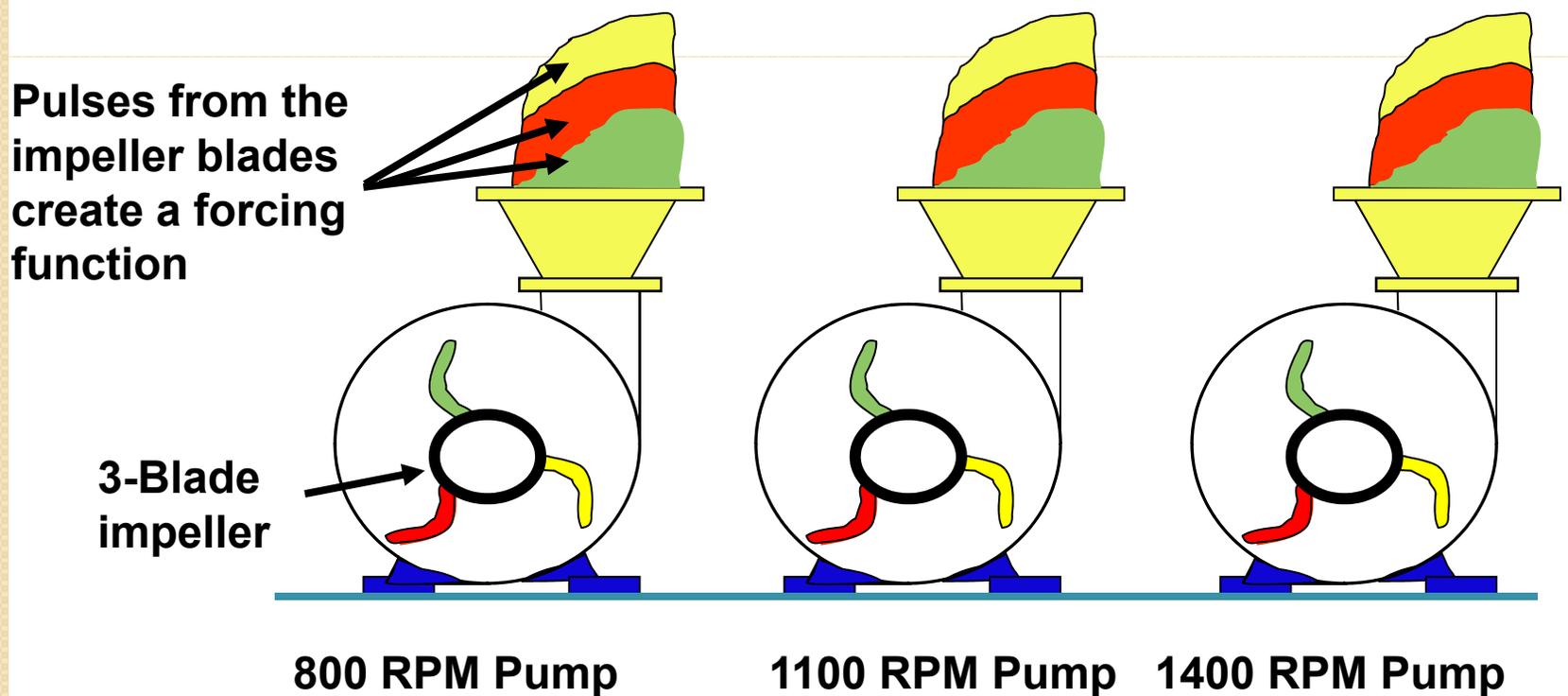


Pulses from the impeller blades create a forcing function at (BPF).

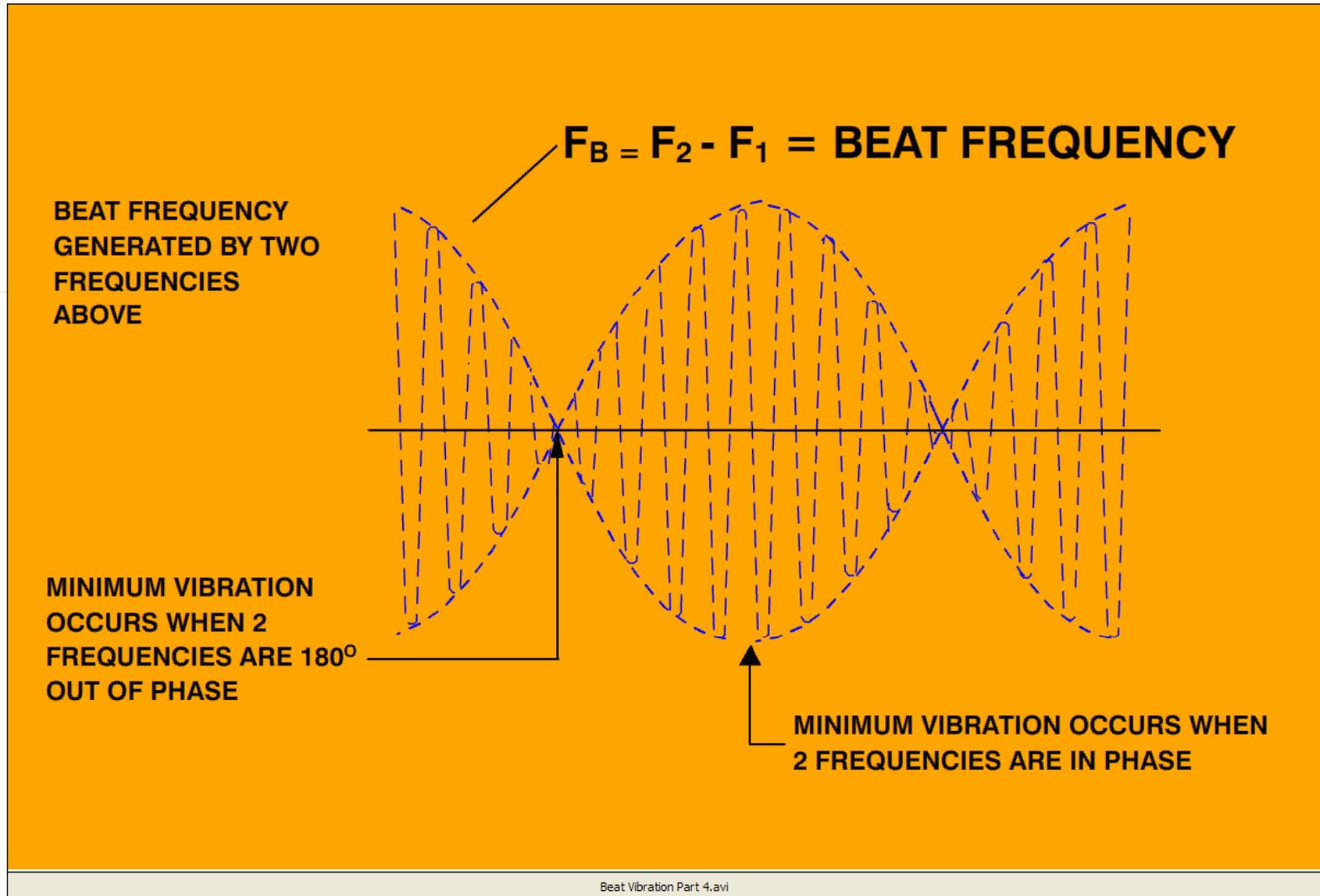


## Notes:

A “Forcing Frequency” is created by the action of a forcing function of a machine component (Pump Blade Pass Frequency BPF) or system occurring at a repetitive rate or periodic event. This is usually expressed in (Hz) or cycles per minute (CPM), or multiples of running speed.

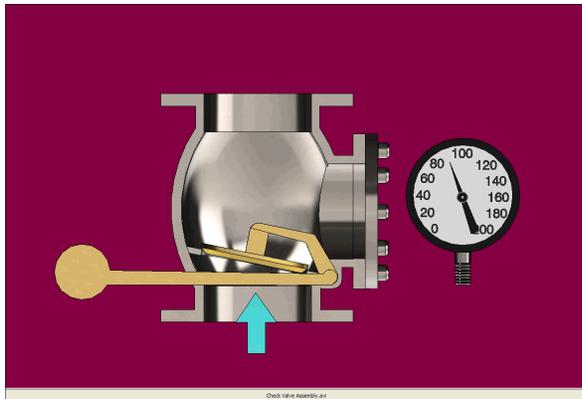


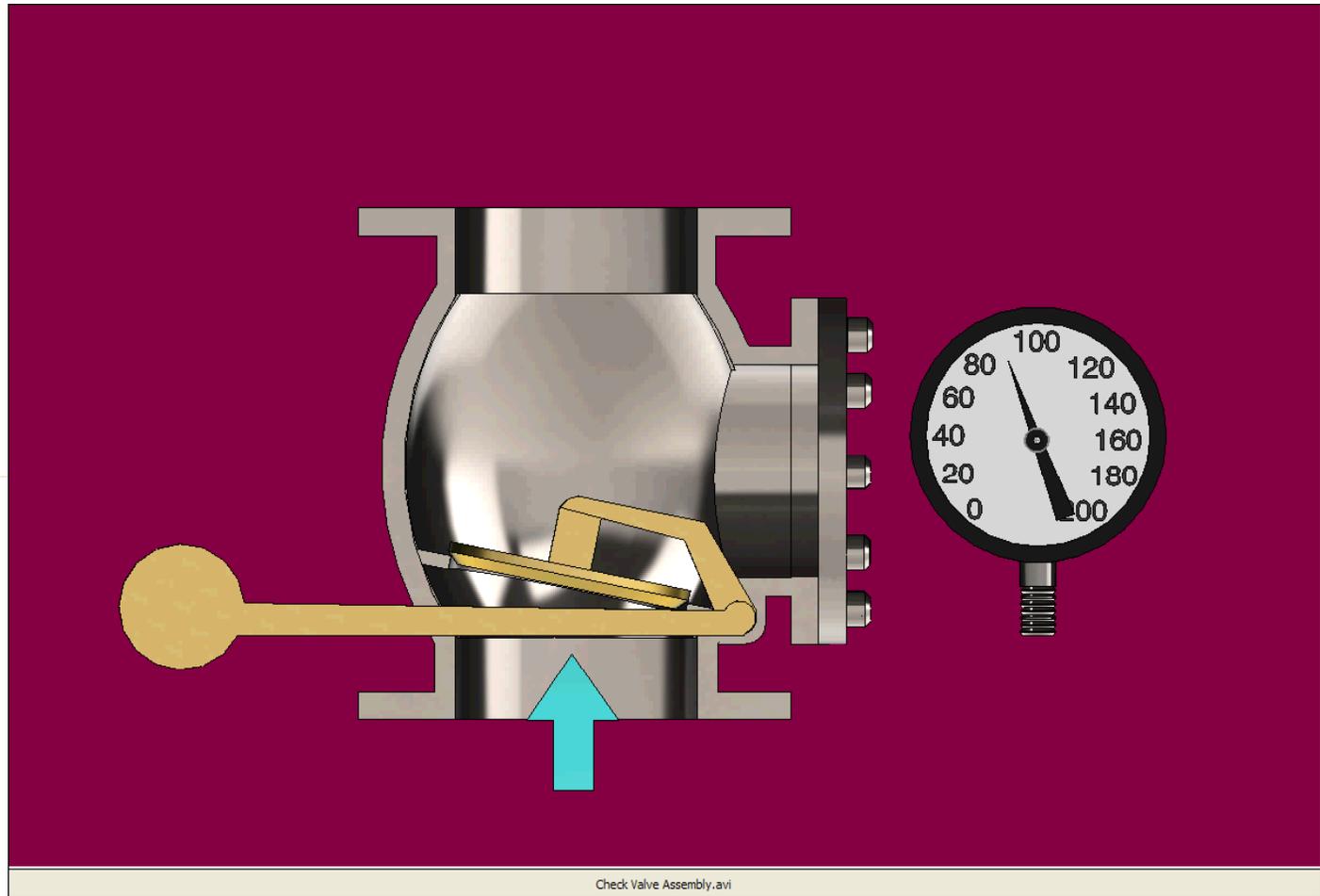
# BEAT FREQUENCY CAN DEVELOP BETWEEN PUMPS OR PRESSURE PULSES



# How Healthy Are Your Pumps?

1. What do you see in the vibration spectra?
2. Is the pump running quiet or noisy? Does it sound like rocks are being pumped?
3. Are the pressures correct and the gauges steady?
4. Are your check valves and piping stable or bouncing and vibrating?
5. Is the amperage on the motor correct or fluctuating?





**Swing Check Valve & Pressure Gauge Bouncing  
Indicates Flow Pulsation /Cavitation**

# **PUMP SYSTEM PROBLEMS?**

## **PUMP DISCHARGE PIPING:**

- 1. Clogged filters, Clogged pipes, Valves closed**
- 2. Discharge piping too small for the flow required**
- 3. Poor piping design, sharp turns and obstructions**
- 4. Incorrect Pump Head calculations.**
- 5. The Pump is operating at or near shutoff head.**

## **SYMPTOMS:**

- 1. Low or fluctuating flow rate.**
- 2. High discharge pressure or pressure pulsations.  
(Pressure gauge fluctuates or Check valve arm bouncing)**
- 3. The pump sounds like it has rocks or marbles rolling around inside.**

## **SUCTION SIDE PROBLEMS:**

- 1. Suction Line Too Long (Low NPSHA).**
- 2. Suction Line clogged or too small.**
- 3. Suction filter/screen clogged.**
- 4. Suction Lift too High**
- 5. Poor inlet piping design**

### **Symptoms:**

**The Pump Sounds Like It's Pumping Rocks,  
Low or pulsing discharge pressure (pressure  
gauge fluctuates)**

**CAVITATION.....MOST LIKELY VAPORIZATION  
TYPE (Classic Type)**



# ***CASE STUDY***

## ***Horizontal End Suction Centrifugal Pumps:***

### **CAVATION PROBLEMS**

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## ***DEFINING THE PROBLEM***

### **Background:**

- ❖ **Four (4) new 125 HP Horizontal End Suction VFD (variable speed 1075-1790 RPM) Centrifugal pumps were installed to replaced older fixed speed pumps that had cavitation issues.**
- ❖ **The pumps are used during high flow conditions and are pumping waste water (sewer).**
- ❖ **The pumps were installed using the existing piping check valves and components.**
- ❖ **The pumps are VFD driven with 14.5” Diameter Impellers (Capable of 210 ft head at 1790 RPM).**
- ❖ **The pumps are designed for solids handling.**

4. The New Pumps were factory tested using clean water for acceptance at all running speeds and heads. 1024 GPM @ 208 ft head was the design selection.

PERFORMANCE TEST		
FLOW GPM 1790 RPM	Hdiff (FT)	Selected Pump has 14.5" Impeller
1. 6	247.4	
2. 662	221.1	
3. 1094	208.0	← 1024 GPM @ 208 ft head 1790 RPM
4. 1104	208.5	
5. 1443	197.2	
6. 1950	181.6	
7. 2341	167.4	

**CLEAN WATER**

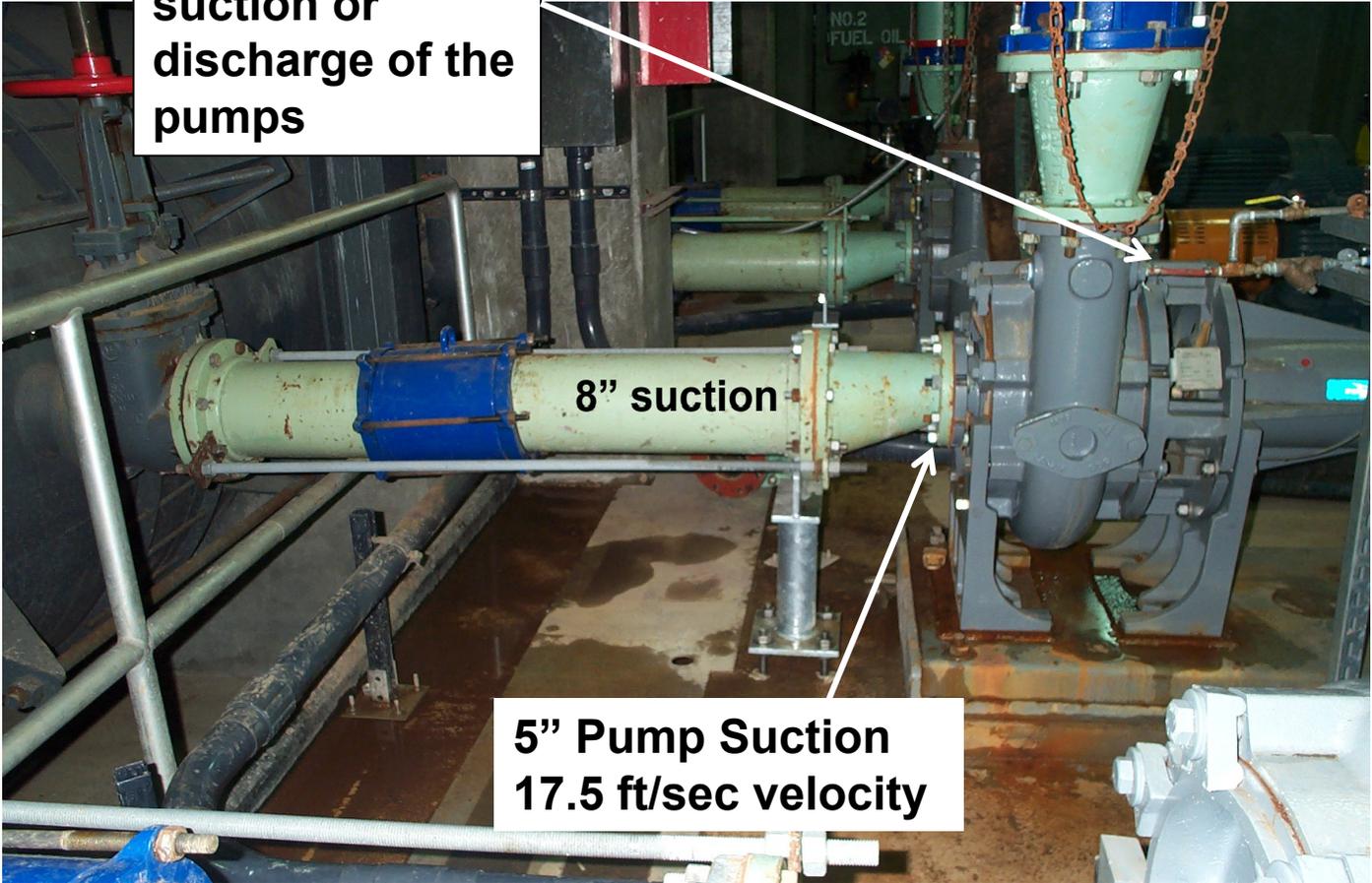


**❖ Technical Associates was contracted to perform standard acceptance testing based upon Hydraulic Institute standards.**

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**THE PUMPS WERE INSTALLED USING THE EXISTING SUCTION PIPING AND VALVES**

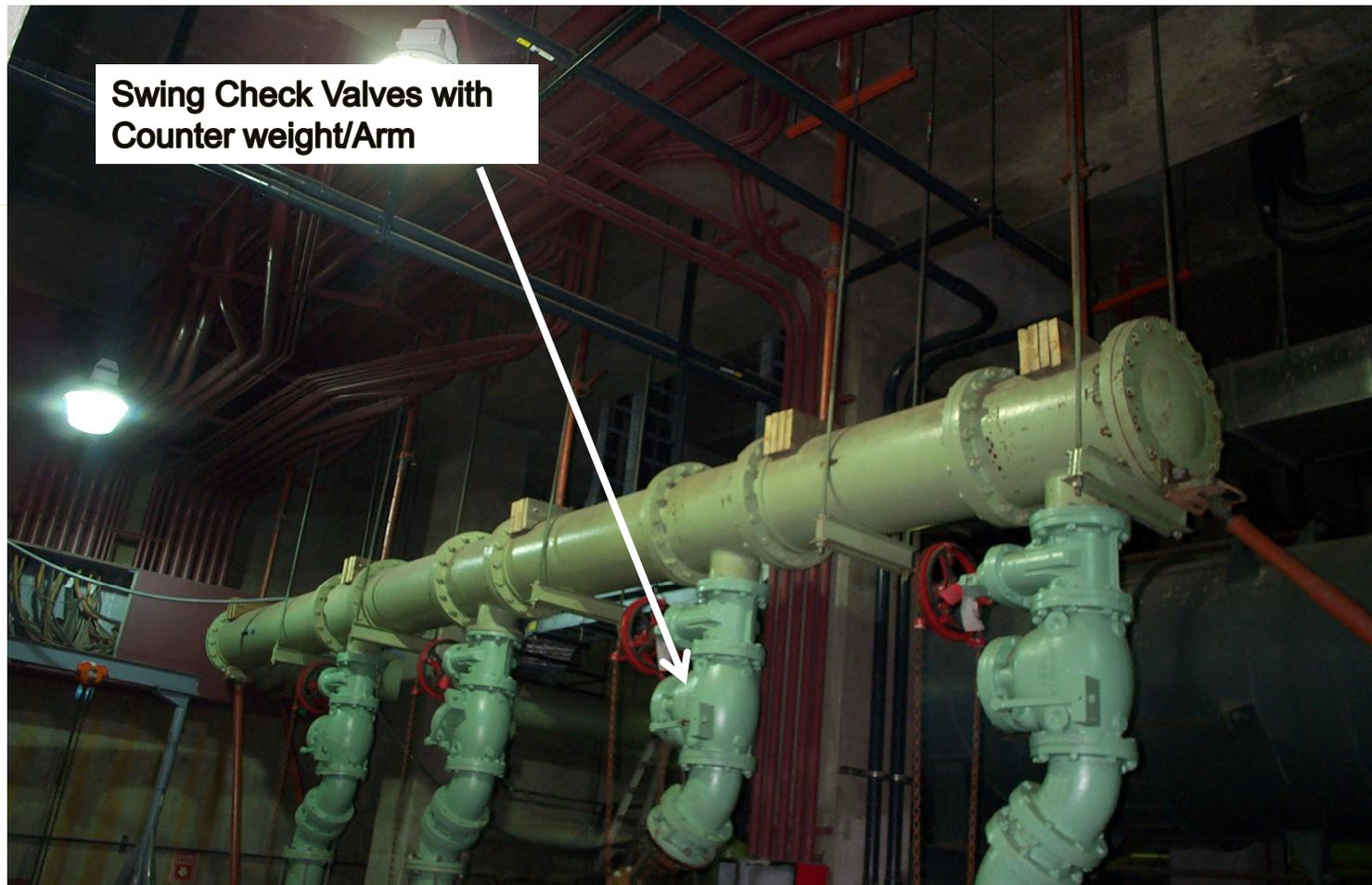
**No pressure gauges on the suction or discharge of the pumps**



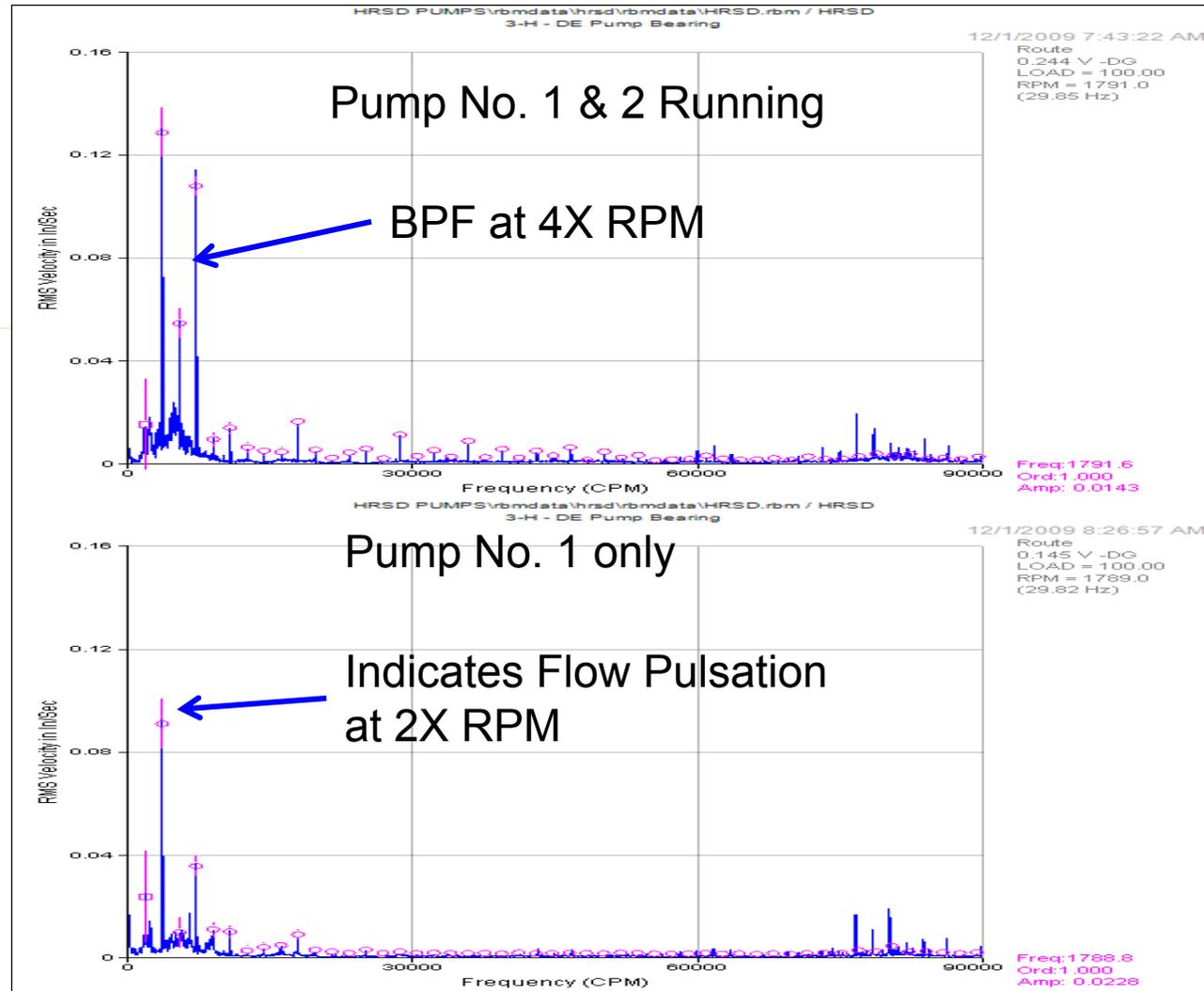
**5\" Pump Suction  
17.5 ft/sec velocity**

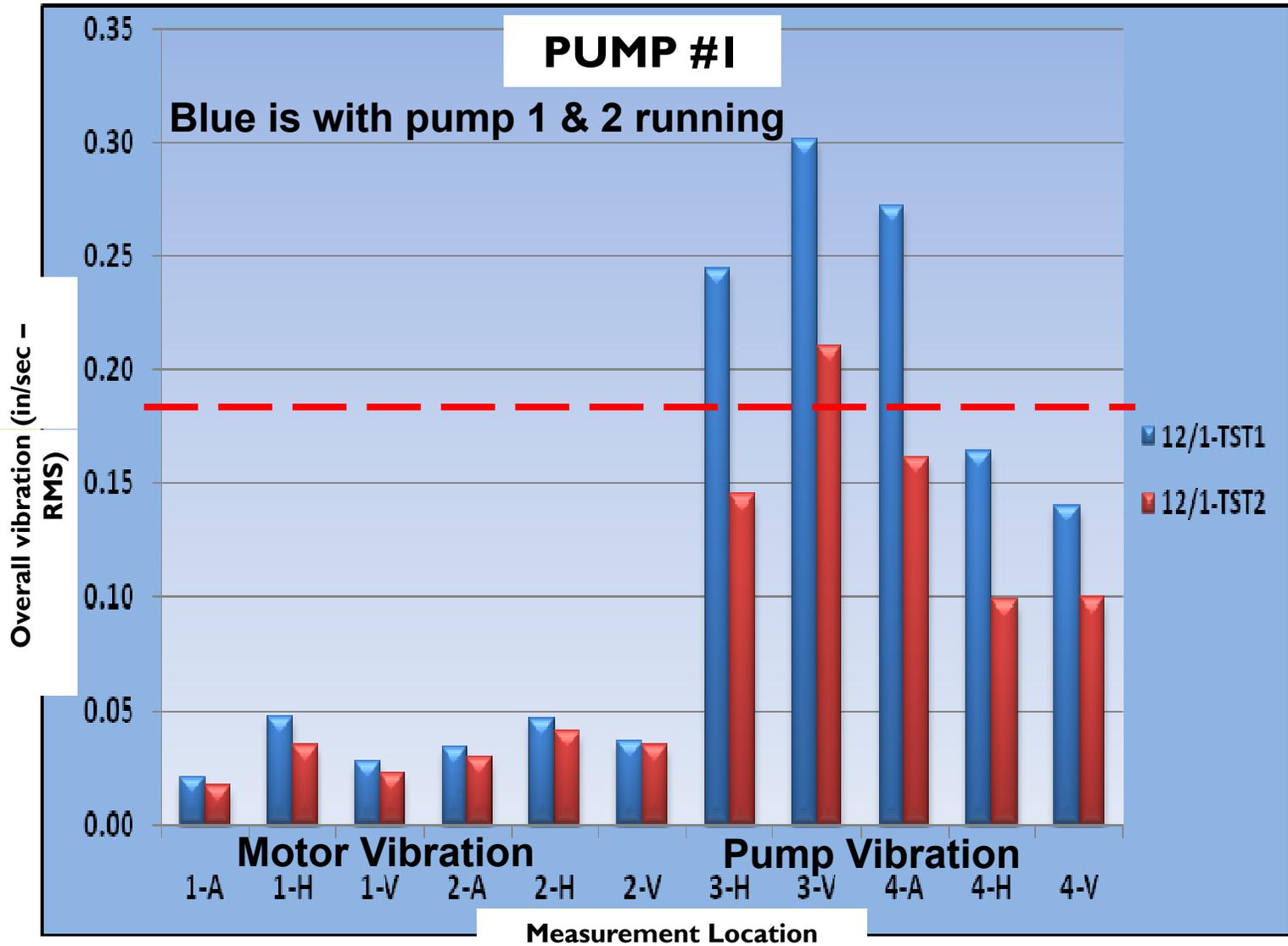
# EXISTING DISCHARGE PIPING HEADER COMMON TO ALL 4 PUMPS

*Each pump is equipped with a check valve (weighted Swing Type)*



# Vibration Data Taken For Acceptance Testing Indicated Turbulence and Possible Cavitation.





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- ❖ Review of the vibration data indicates the pumps are experiencing cavitation. The cavitation increases when two (2) pumps operate and is reduced when one pump operates.
  - ❖ Operation of 2 pumps increases the pump noise (cavitation sounds). This indicates the pumps are sensitive to discharge pressure changes causing cavitation.
  - ❖ The pumps have no pressure gauges.
  - ❖ This makes it difficult to determine how they are operating.

❖ The pumps have a 14.5” diameter impellers and a 5” Diameter inlet connection. At design flow of 1024 GPM the velocity at the impeller inlet is 17.5 ft/sec. This was determined by Inspection of the impeller after failure of pump # 1.

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❖ **“Rule of Thumb” from experience:**  
Target 10-12 ft/sec velocity at the pump suction. Maybe stretching to 12.5-15 ft/sec, but never over.

## •CONCLUSIONS

### Pump #1

Three locations on pump #1 exceed the allowable overall vibration level of 0.18 in/sec RMS when both pumps were operated simultaneously. The remaining measurement locations on the pump and motor are below the allowable overall vibration level.

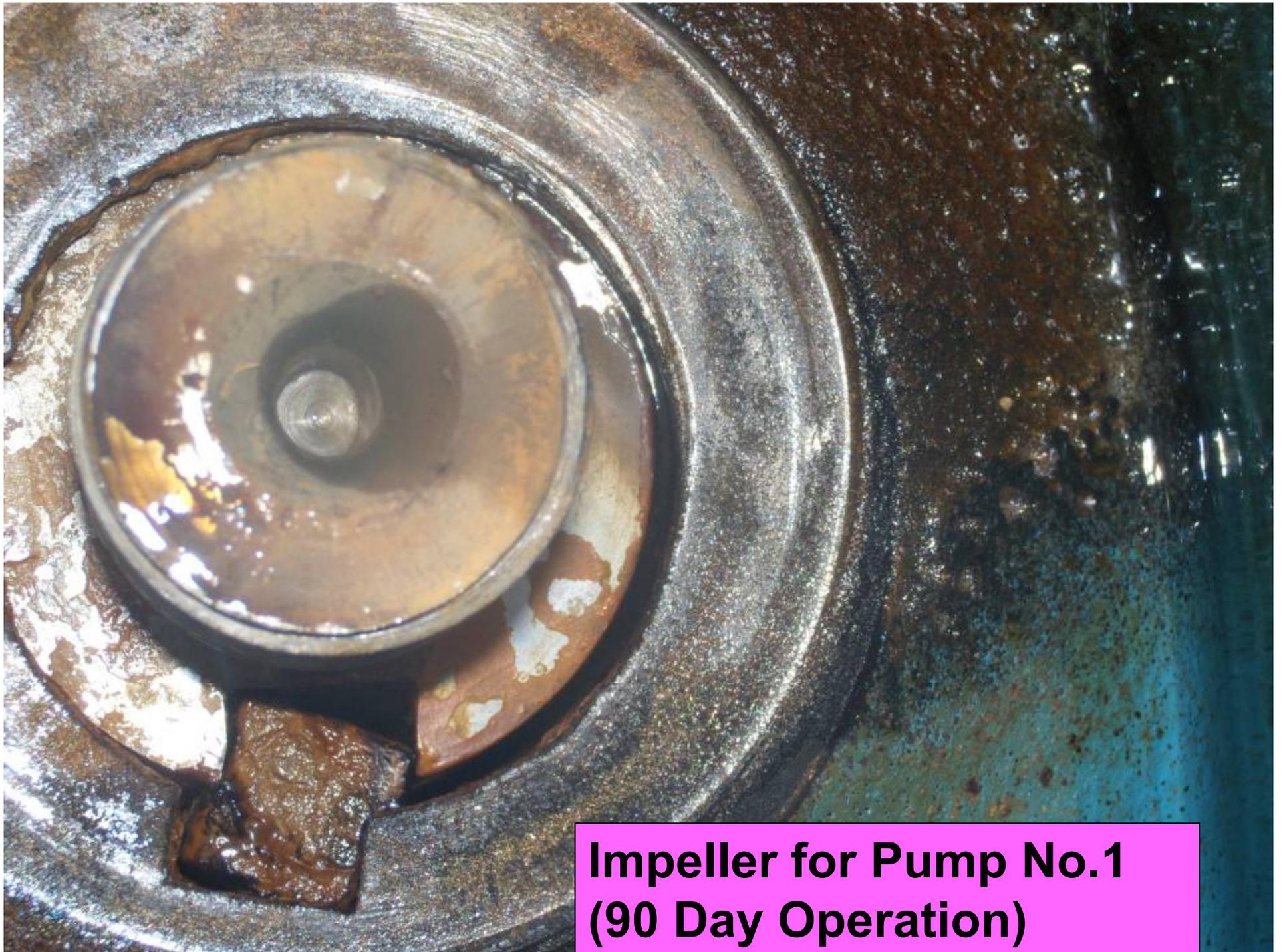
Only one measurement location, (pump drive end vertical) exceeds the allowable overall vibration level of 0.18 in/sec RMS when only pump #1 was operated and pump #2 was stopped.

**Spectral analysis of the vibration data indicates that cavitation effects are evident during operation.**

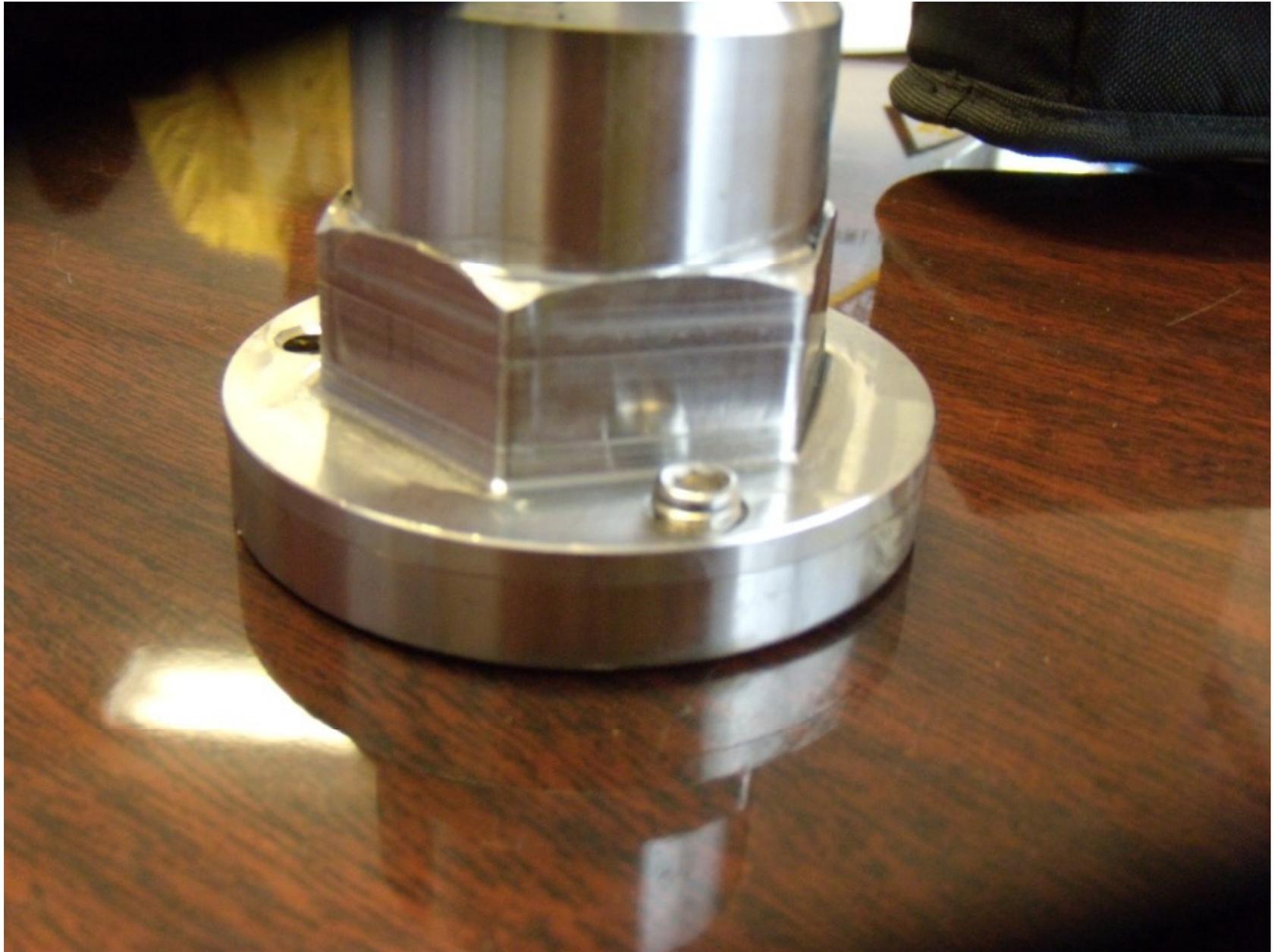
**THE PUMPS FAILED ACCEPTANCE TESTING**

## **The Utility decided to continue operating the pumps on a part time basis.**

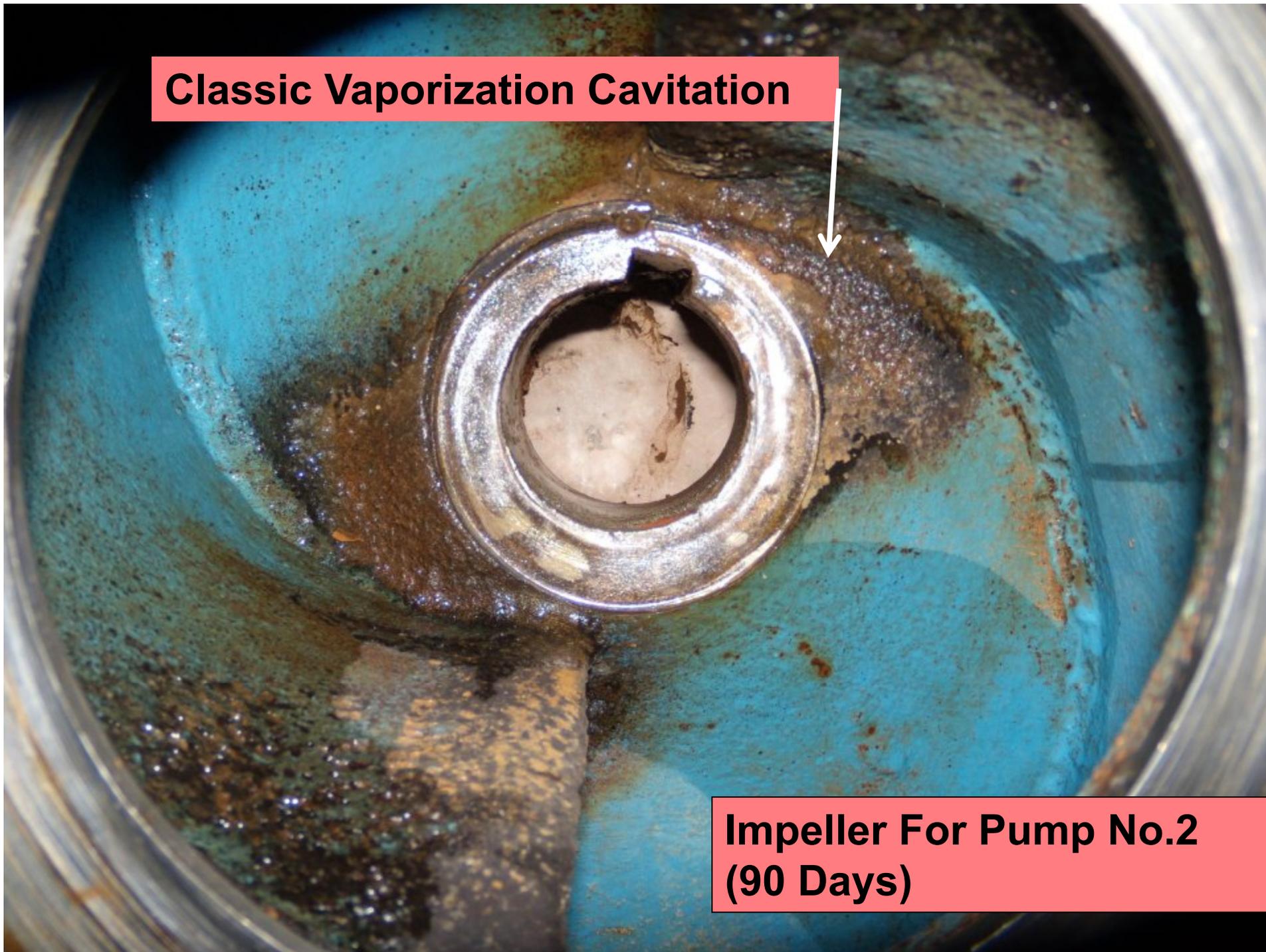
- ❖ Pump # 1 Catastrophically failed after approximately 90 days of part time operation.
- ❖ Pump # 2 Was examined and found to have similar cavitation damage as pump #1.
- ❖ Plant engineers and management examined the pump impeller and housing. From the pictures and physical examination it was concluded that cavitation was the problem. They had decided that air entrained in the suction piping was the problem.



**Impeller for Pump No.1  
(90 Day Operation)**

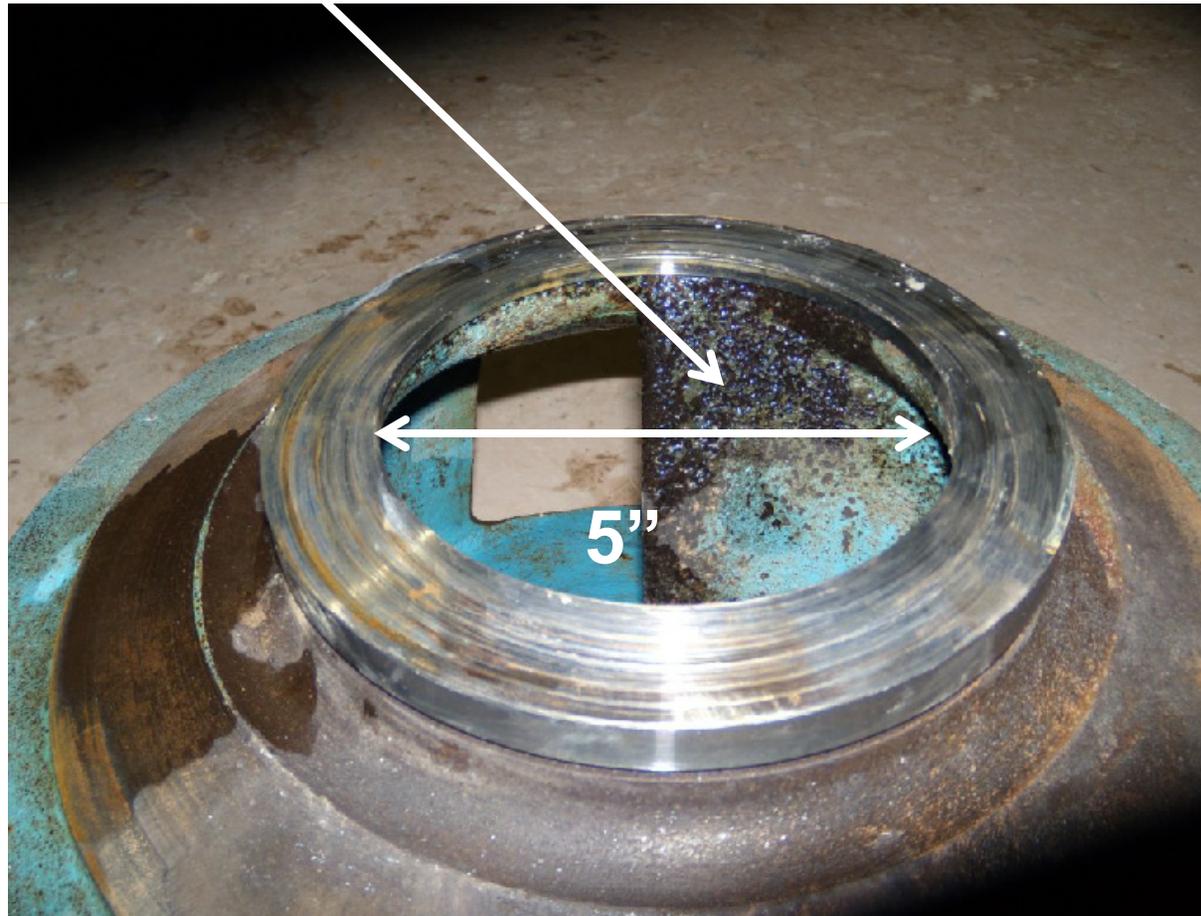


**Classic Vaporization Cavitation**



**Impeller For Pump No.2  
(90 Days)**

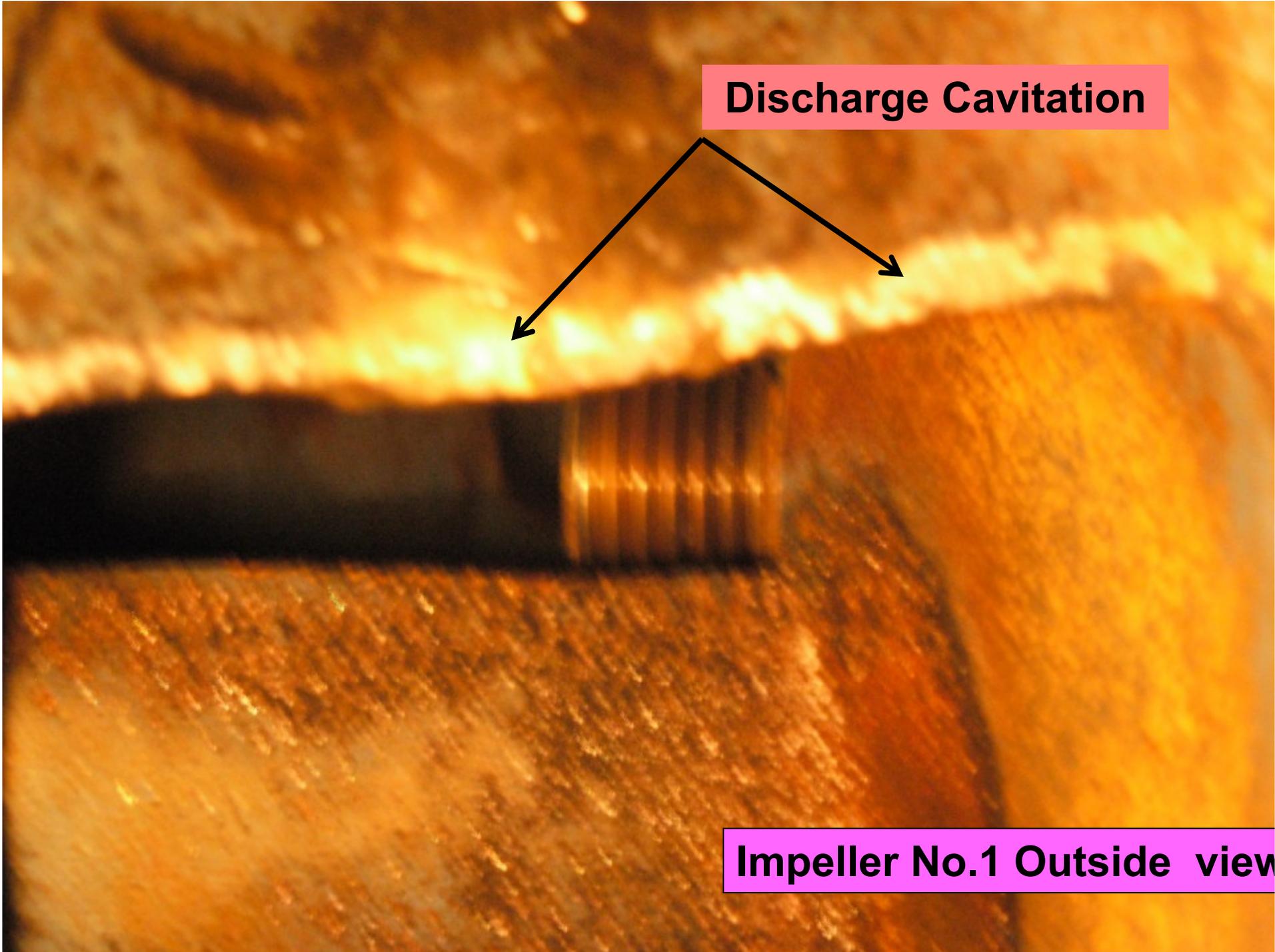
- ❖ The pumps have a 14.5" diameter impellers and a 5" Diameter inlet connection. At design flow of 1024 GPM the velocity at the impeller inlet is 17.5 ft/sec. Inspection of pump # 1 impeller after failure.

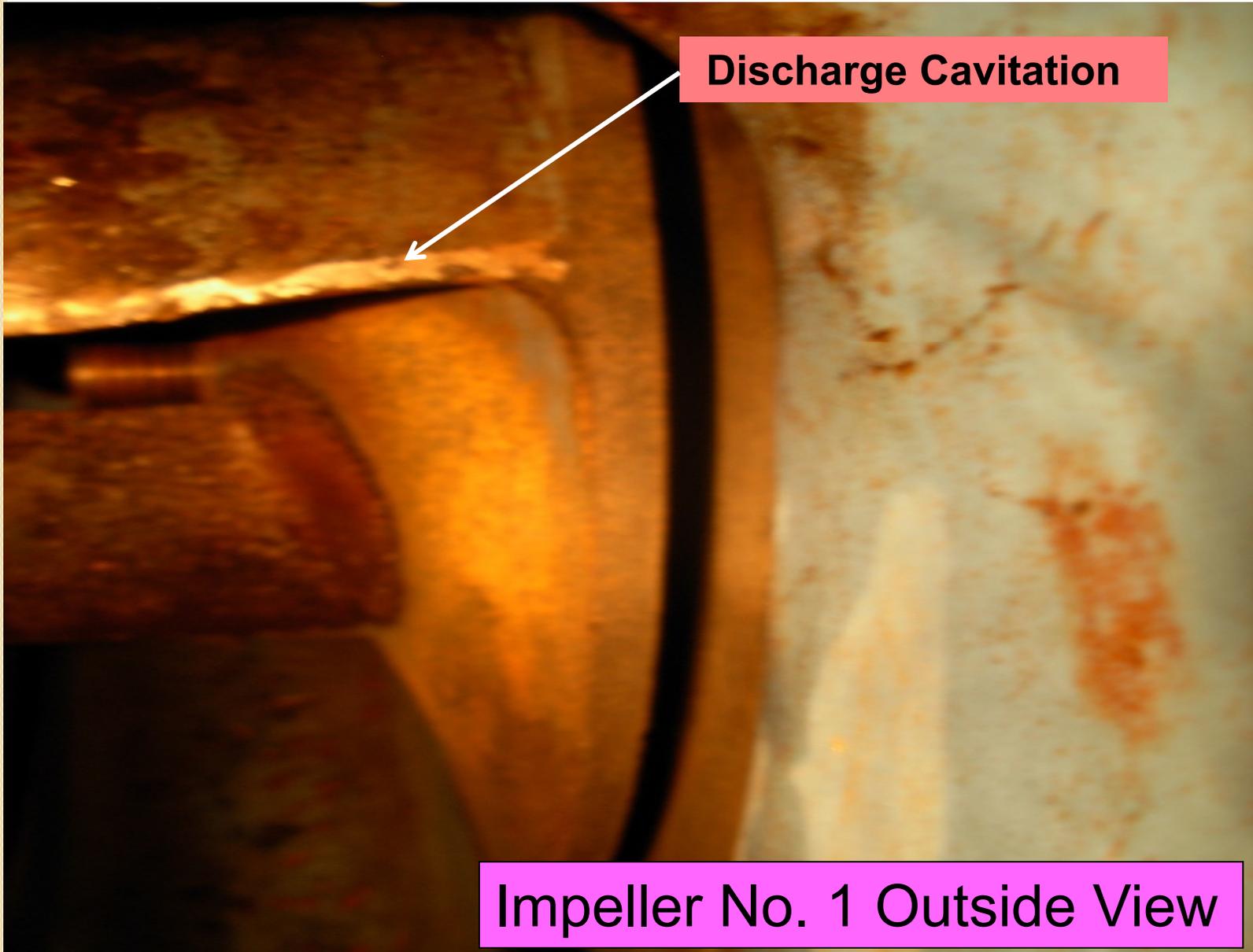


**Discharge Cavitation**



**Impeller No.1 Outside view**





**Discharge Cavitation**

**Impeller No. 1 Outside View**



Plant engineers and management decided the problem was “Air In The Suction Line” and fluid swirl causing classic vaporization cavitation.

A consultant was hired to investigate the problem using plastic pipe and video.

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Pumptest.mov

Technical Associates was contracted to perform a diagnostic investigation on pumps 3 &4.

## **First Conclusions After Failure Of Pump # 1:**

1. The pump and piping system have problems.
2. The vibration data taken indicates cavitation.
3. The check valve bouncing and pressure gauge indicates flow pulsation.
4. Flow pulsation in conjunction with cavitation are the suspected problems.

### **Questions:**

1. Is the flow pulsation caused by the cavitation?
2. How can we further diagnose the problems?

## **FIRST RECOMMENDATIONS:**

- 1. Review the performance test data supplied by the pump manufacturer.**
- 2. Install pressure gauges on the suction & discharge piping at the pumps.  
A pressure gauge at the suction will provide information for NPSHA calculations.  
(Positive 3 psi)**
- 3. The pressure gauge at the pump discharge will help estimate the total head the pump is working against.  
Total Head ft = (discharge psi - suction psi) x 2.31**
- 4. Conduct field (as installed) test for the pumps at different running speeds. Recording pressure, flow and cavitation noise.**

# FIELD TEST RESULTS WITH GAUGES IN PLACE PUMPS 3 & 4:

Original Pump Selection 1024 GPM  
at 208 ft. Head

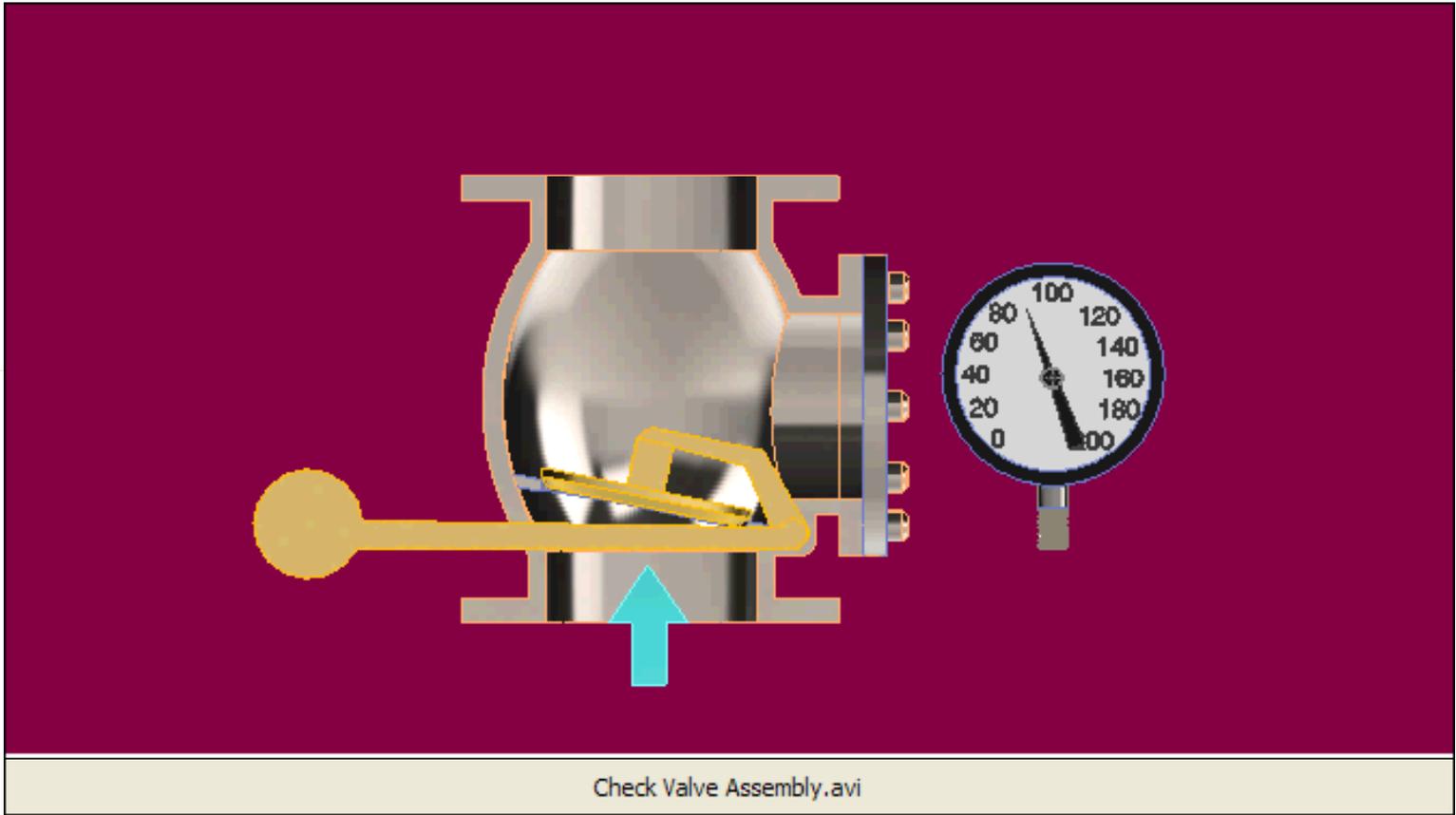
Discharge PSI  
Suction PSI

$$TDH = (Dpsi - Spsi) \times 2.31$$

Pump	Speed	Flow			TDH	Observations
3	1790	776	101 <sub>±</sub>	2	228	Sound of rocks inside Check & PG Bouncing
4	1790	776	101 <sub>±</sub>	2	228	Sound of rocks inside Check & PG Bouncing
3	1430	955	62	1.5	139.7	No noise Check & PG not bouncing
4	1430	955	62	1.5	139.7	No noise Check & PG not bouncing
3	1255	825	50	3	109	No noise Check & PG not bouncing
4	1255	825	50	3	109	No noise Check & PG not bouncing

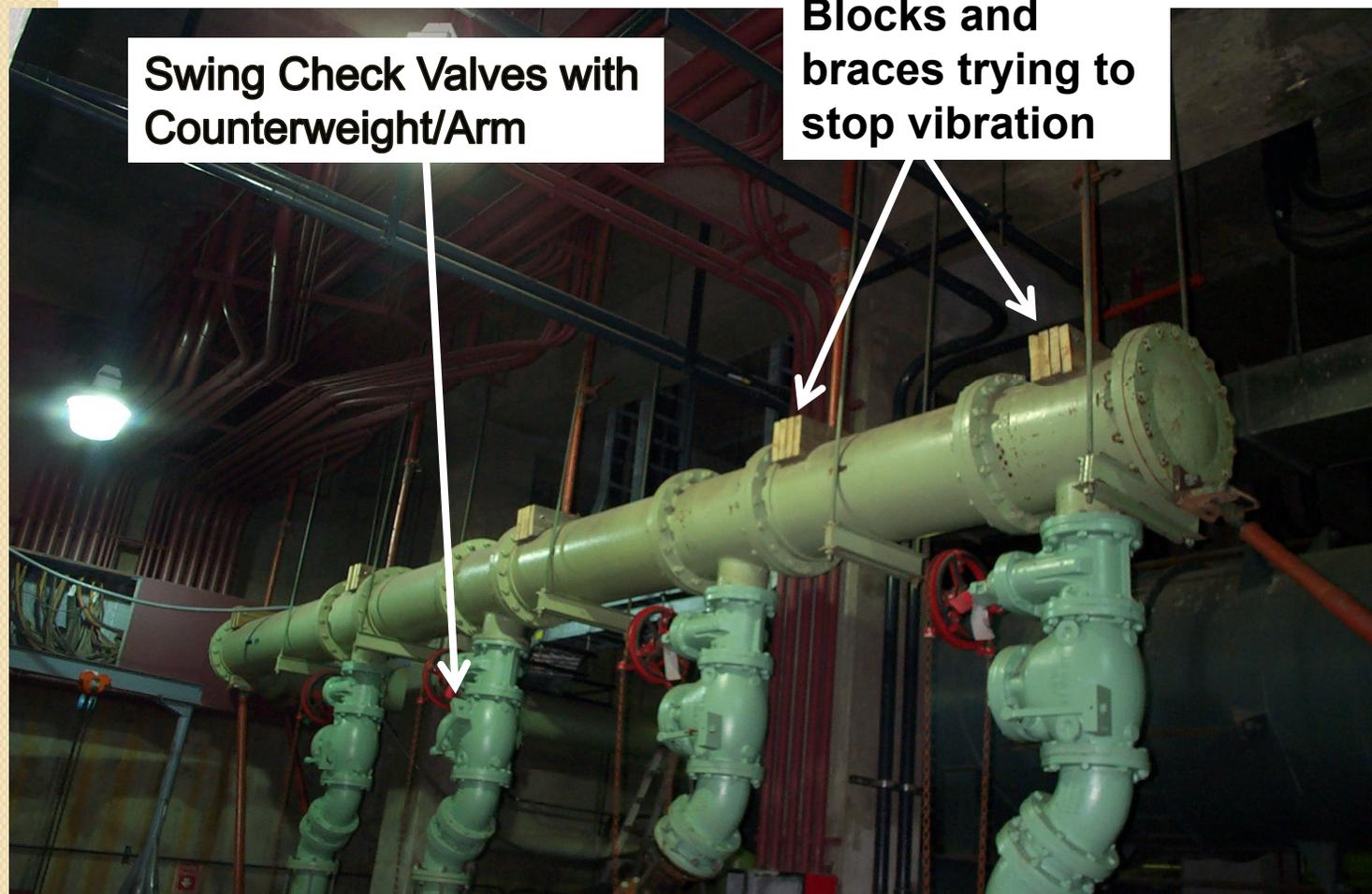
## **Conclusions following Test:**

- 1. The pumps (3 & 4) and piping system have problems at running speeds above 1500 RPM.**
- 2. The vibration data indicates cavitation at running speeds above 1500 RPM. The pumps sound like they are pumping rocks.  
(Raised noise floor Superimposed with BPF).**
- 3. The swing check valve (external counterweight) at the discharge of each pump is bouncing up & down at higher running speeds causing pipe vibration. Additionally, the flow pulsation is an indicator of discharge cavitation at higher speeds.**



## Swing Check Valve with Pressure Gauge

# ***EXISTING DISCHARGE PIPING HEADER COMMON TO ALL 4 PUMPS***



## Final Conclusions:

1. The pumps are suffering from cavitation caused by high impeller velocity and flow velocity at high running speeds. The discharge head is lower than design selection for these pumps. Therefore, the pumps are operating way off their curves.
2. What type of cavitation and why?
3. From visual inspection (pictures) Vaporization cavitation (Classic) caused by churning of the fluid at the impeller inlet and not from inadequate NPSHa (Suction Pressure + 3 psi). **The fluid contains organic material and is prone to generate vapors (Methane Gas) when it is churned.**
4. Discharge Cavitation occurs as the fluid surges back through the impeller with cavitation bubbles impacting the outer tip of the impeller.

**5. Data from field testing of flow and pressure at different running speeds indicate pump performance problems when handling waste water. The pumps are equipped with 14.5” impellers that develop adequate head when pumping alone or with other pumps at running speeds below 1500 RPM.**

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**6. The pulsation of flow through the check valve and pressure fluctuations indicate cavitation at the discharge and vaporization as seen on the damaged impellers.**

## **SOLUTION:**

1. Operate the pumps at 1500 RPM or below. The pumps are capable of developing adequate head and almost the required flow at the lower running speeds.
2. Order new pumps with the correct flow and head selections.



# **MORAL**

**PUMPS ARE BASICALLY  
SIMPLE MACHINES  
BUT CAN BE**

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**A**

**Challenge...!!**

**Thanks for the opportunity to discuss a few  
challenges today.....!!**

**David Kesler**