3 Cavitation

Introduction

It is important to clarify that the pump does not cavitate, although people in the industry tend to say that the pump is cavitating. It is more correct to say that the pump is in cavitation or the pump is suffering cavitation. In reality it is the system that cavitates the pump, because the system controls the pump.

Inadequate NPSHa establishes favorable conditions for cavitation in the pump. If the pressure in the eye of the impeller falls below the vapor pressure of the fluid, then cavitation can begin.

Vapor pressure

Definition

The vapor pressure of a liquid is the absolute pressure at which the liquid vaporizes or converts into a gas at a specific temperature. Normally, the units are expressed in pounds per square inch absolute (psia). The vapor pressure of a liquid increases with its temperature. For this reason the temperature should be specified for a declared vapor pressure.

At sea level, water normally boils at 212°F. If the pressure should increase above 14.7 psia, as in a boiler or pressure vessel, then the boiling point of the water also increases. If the pressure decreases, then the water's boiling point also decreases. For example in the Andes Mountains at 15,000 ft (4,600 meters) above sea level, normal atmospheric pressure is about 8.3 psia instead of 14.7 psia; water would boil at 184°F.

Inside the pump, the pressure decreases in the eye of the impeller because the fluid velocity increases. For this reason the liquid can boil at a lower pressure. For example, if the absolute pressure at the impeller eye should fall to 1.0 psia, then water could boil or vaporize at about 100°F (see the Tables in Chapter 2 Properties of Water I and II).

Cavitation

Definition

Cavitation is the formation and subsequent collapse or implosion of vapor bubbles in the pump. It occurs because the absolute pressure on the liquid falls below the liquid's vapor pressure.

When the vapor bubbles collapse with enough frequency, it sounds like marbles and rocks are moving through the pump. If the vapor bubbles collapse with enough energy, they can remove metal from the internal casing wall, and leave indent marks appearing like blows from a large ball pein hammer.

This book is dedicated to pumps but we should mention that cavitation could occur in other parts of the pumping system. Under the correct circumstances, valves and pipe elbows are also candidates to suffer damage from cavitation.

The effects of vapor pressure on pump performance

When cavitation occurs in a pump, its efficiency is reduced. It can also cause sudden surges in flow and pressure at the discharge nozzle. The calculation of the NPSHr (the pump's minimum required energy) and the NPSHa (the system's available energy), is based on an understanding of the liquid's absolute vapor pressure.

The effects of cavitation are noise and vibration. If the pump operates under cavitating conditions for enough time, the following can occur:

- Pitting marks on the impeller blades and on the internal volute casing wall of the pump.
- Premature bearing failure.
- Shaft breakage and other fatigue failures in the pump.
- Premature mechanical seal failure.

These problems can be caused by:

- A reduction of pressure at the suction nozzle.

- An increase of the temperature of the pumped liquid.
- An increase in the velocity or flow of the fluid.
- Separation and reduction of the flow due to a change in the viscosity of the liquid.
- Undesirable flow conditions caused by obstructions or sharp elbows in the suction piping.
- The pump is inadequate for the system.

The focus should be on resolving cavitation problems by increasing the external pressure on the fluid or decreasing its vapor pressure. The external pressure could be increased by:

- Increasing the pressure at the pump suction.
- Reducing the energy losses (friction) at the entrance to the pump.
- Using a larger pump.

The vapor pressure of the fluid is decreased by:

- Lowering the temperature of the fluid.
- Changing to a fluid with a lower vapor pressure.

At times, simply removing aspirated air venting the pump will have the same effect.

Cavitation: A practical discussion

Consider the following

I need a pump to raise cold water at 10 gallons per minute. There is an open well with water 40 ft below ground level.

- Do I need a PD Pump?
- Do I need a Centrifugal Pump?
- Should the pump be small, medium, or large?

The reply

No pump in the world can lift cold water 40 ft from an open well in a suction lift condition because the water would evaporate before it comes into the pump. The reason lies in the basic head formula:

$$H = \frac{\text{psi} \times 2.31}{\text{sp. gr.}}$$

$$= \frac{14.7 \text{ psi} \times 2.31}{1.0}$$

$$= 33.9 \text{ ft}$$

You can only raise a column of cold water in a pipe a maximum of 33.9 ft with a pump in suction lift. Beyond 34 ft, the water will boil or vaporize. This is the reason why submersible pumps and vertical turbine pumps exist. There is no limit to the distance you can push a liquid from below, but you can only aspirate a liquid a maximum of 34 ft from below the pump.

AUTHOR'S NOTE

Question: If you put a straw into a glass of milk and suck on the straw, are you really sucking on the milk?

Reply: If you could really suck on the milk, then you wouldn't need the straw. What you're actually doing with your mouth on the straw is lowering the atmospheric pressure inside the straw, so that the atmospheric pressure outside the straw pushes the milk up into your mouth. This is why we say that a pump does not suck. The pump actually generates a zone of low pressure in the eye of the impeller, thereby lowering the atmospheric pressure inside the suction piping. Atmospheric pressure outside the suction piping pushes the liquid up toward the impeller a maximum of 34 ft under ideal circumstances.

Holes in the liquid (cavitation)

A cavitation bubble is a hole in the liquid. If I should have bubbles in the suction of my pump then I have problems. Pumps can move liquid, but they cannot move air or gas bubbles. Compressors exist for moving gases. A gas will not centrifuge. Bubbles occupy space inside the pump and affect the pump's pressure and flow. With vapor bubbles in the low-pressure zones of the pump, the motor's energy is wasted expanding the bubbles instead of bringing more liquid into the pump. As the bubbles pass into the pump's high-pressure zones, the motor's energy is wasted compressing the bubbles instead of expelling the liquid from the pump. The bubbles can collapse as they pass from low- to high-pressure zones in the pump. The water is rather hard.

AUTHOR'S NOTE

You'll know this if you've ever done a belly flop into a swimming pool.

When vapor bubbles collapse inside the pump the liquid strikes the metal parts at the speed of sound. This is the clicking and popping noise we hear from outside the pump when we say that cavitation sounds like pumping marbles and rocks. Sound travels at 4,800 ft per second in water. The velocity head formula gives a close approximation of the energy contained in an imploding cavitation bubble. Remember that implosion is an explosion in the opposite direction.

Using the velocity head formula:

$$H_v = \frac{V^2}{2g}$$

$$= \frac{(4{,}800 \text{ FT/SEC})^2}{2 \times (32.16 \text{ FT})}$$

$$= \frac{23{,}040{,}000}{64.32}$$

$$= 358{,}209 \text{ ft}$$

In pump terminology, the approximate energy in an imploding cavitation bubble is 358,209 ft. To convert this energy into pressure:

$$\text{Pressure in psi} = \frac{\text{Head} \times \text{Sp. gr.}}{2.31}$$

$$= \frac{358{,}209 \times 1.0}{2.31}$$

$$= 155{,}069 \text{ psi}$$

You can see, based on the velocity head formula, a cavitation bubble impacts the impeller and other pump parts at about 155,069 psi. Other experiments in test laboratories using a more precise rHv, have calculated the impact pressure at 1 Gigapascal, or 147,000 psi. This is the reason that the damage from cavitation appears like someone was beating on your impeller with a large ball pein hammer.

AUTHOR'S NOTE

In medicine, doctors use this same energy contained in cavitation bubbles (Lithotripsy) to treat and destroy kidney stones and tumors. The bubbles act like microscopic jackhammers, disintegrating kidney stones.

If your pump is in cavitation, you'll have one or more of the following:

- Problems with pump packings.
- Problems with mechanical seals.
- Problems with alignment.
- Problems with the bearings.
- Problems with impellers, casings, and wear bands.
- Problems with pump efficiency.
- Problems with leaks and fugitive emissions.

And these problems won't go away until you resolve **cavitation** at its source.

There are five recognized types of cavitation:

- Vaporization cavitation, also called inadequate NPSHa cavitation
- Internal re-circulation cavitation.
- Vane passing syndrome cavitation.
- Air aspiration cavitation.
- Turbulence cavitation.

Let's investigate each of these, their causes and resolutions:

Vaporization cavitation

Vaporization cavitation represents about 70% of all cavitation. Sometimes it's called 'classic cavitation'. At what temperature does water boil? Well, this depends on the pressure. Water will boil if the temperature is high enough. Water will boil if the pressure is low enough.

According to Bernoulli's Law, when velocity goes up, pressure goes down. This was explained in Chapter 1. A centrifugal pump works by acceleration and imparting velocity to the liquid in the eye of the impeller. Under the right conditions, the liquid can boil or vaporize in the eye of the impeller. When this happens we say that the pump is suffering from vaporization cavitation.

This type of cavitation is also called inadequate NPSHa cavitation. To prevent this type of cavitation, the NPSHa in the system (the available energy in the system), must be higher than the NPSHr of the pump (the pump's minimum energy requirement).

A good suggestion to prevent vaporization cavitation is:

NPSHa > NPSHr + 3 ft or more safety margin

AUTHOR'S NOTE

Remember from Chapter 2, the NPSHa formula is: NPSHa = Ha + Hs – Hvp – Hf – Hi. If you want to raise the NPSHa, it will be necessary to increase the elements (Ha, Hs) that add energy to the fluid, or decrease the elements (Hvp, Hf, Hi) that rob energy from the fluid. Also remember that the NPSHr reading, printed on a pump curve, currently represents a point where the pump is already suffering a 3% loss in function due to cavitation. Some people in the industry are calling for a more precise definition of NPSHr, and higher safety margins on NPSHa.

With the pump disassembled in the shop, the damage from vaporization cavitation is seen behind the impeller blades toward the eye of the impeller as illustrated below (Figure 3–1).

To resolve and prevent this type of cavitation damage:

1. Lower the temperature. This reduces the **Hvp**
2. Raise the liquid level in the suction vessel. This elevates the **Hs**.
3. Change the pump.
   - Reduce the speed. This reduces the **Hf**.
   - Increase the diameter of the eye of the impeller. This reduces **Hf** and **Hi**.
   - Use an impeller inducer. This reduces the **Hi**, and increases **Ha**.
   - Use two lower capacity pumps in parallel. This reduces **Hf** and **Hi**.
   - Use a booster pump to feed the principal pump. This increases the **Ha**.

A typical situation often resulting in vaporization cavitation is a boiler

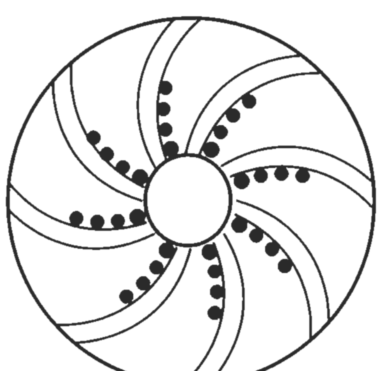

Figure 3-1

feed water pump where the pump drains the deaerator (d-a) tank. Because this pump generates high discharge pressure, it must also generate a strong vacuum in the eye of the impeller. Typically, this pump can generate 200 psi (460 ft of head) and require 30 ft of NPSHr at its duty point.

The d-a tank is normally one of two varieties:

- Vented and exposed to atmosphere.
- Closed and pressurized.

Once again, the formula and elements of NPSHa are:

NPSHa = Ha + Hs – Hvp – Hf – Hi, where:

Ha Atmospheric Head. It is 33.9 ft at sea level.

Hs Static Head. It is the level in the d-a tank above the pump centerline. This is normally about 12 to 15 ft.

Hvp Vapor Head. It is based on the feed water temperature. See Chapter 2, Properties of Water I and II.

Hf Friction Head, or the friction losses in the suction piping. We could assign this a value of 1 ft.

Hi Inlet Head. The losses in the pump suction throat to the impeller eye. These losses could be insignificant up to 2 ft, depending on design.

The feed water in the d-a tank normally runs about 190°F in an open tank. Then we have:

NPSHa = 33.9 + 15 – 22 – 1 – 2
NPSHa = 23.9 ft

if the feed water temperature should be 205°F:

NPSHa = 33.9 + 15 – 30 – 1 – 2
NPSHa = 15.9 ft

if the d-a tank should be closed, then the Ha = Hvp. Therefore they cancel:

NPSHa = 15 – 1 – 2
NPSHa = 12 ft

If the d-a tank should be sealed and artificially pressurized with steam gas (sometimes they are, or should be), then each 10 psi adds 23.1 ft of artificial head to the system's NPSHa. If the boiler feed water pump has a NPSHr of 30 ft at the duty point, now you can see why boiler feed water pumps are sometimes considered problematic regarding cavitation. This also demonstrates the need to seal and artificially pressurize d-a tanks to get the NPSHa above the NPSHr of the pump.

Internal re-circulation

This is a low flow condition where the discharge flow of the pump is restricted and the product cannot leave the pump. The liquid is forced to re-circulate from high-pressure zones in the pump into low-pressure zones across the impeller.

This type of cavitation originates from two sources. First, the liquid is circulating inside the volute of the pump at the speed of the motor and it rapidly overheats. Second, the liquid is forced to pass through tight tolerances at very high speed. (These tight tolerances are across the wear bands on enclosed impellers, and between the impeller's leading edges and the volute casing on opened impellers.) The heat and the high velocity cause the liquid to vaporize.

With the pump disassembled in the shop, with open impellers, the damage is seen on the leading edge of the impeller blades toward the eye of the impeller, and on the blade tips toward the impeller's OD. With enclosed impellers, the damage reveals itself on the wear bands between the impeller and the volute casing. See the illustration (Figure 3–2).

To correct this condition with an opened impeller, it's necessary to perform an impeller adjustment to correct the strict tolerance between the blades and the volute. Some back pullout pumps are designed with jack bolts on the power end of the bearing housing to easily perform this adjustment without pump disassembly.

This condition cannot be corrected on pumps with an enclosed impeller. You need to relax the restricted discharge flow on the pump. The problem could be a clogged downstream filter, a closed discharge valve, an over-pressurized header (back-pressurizing the pump), or a

The damage is seen on the leading edge of the impeller blades toward the eye of the impeller, and on the blade tips toward the impeller's OD.

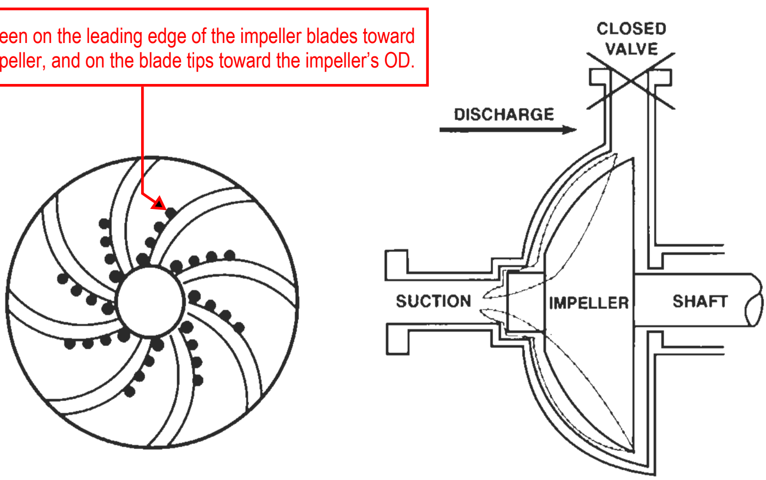

Figure 3–2

check valve installed backwards, or operating the pump at or close to shut-off head. Maybe a variable speed motor could help under certain circumstances.

The vane passing syndrome

The vane passing syndrome can exist when the blade tips at the OD of the impeller are passing too close to the cutwater on the pump casing. This can be caused by exchanging an impeller for a larger diameter impeller, or from re-metalizing or coating the internal housing of the pump. The free space between the impeller blade tips and the cutwater should be 4% of the impeller diameter (Figure 3–3).

With the pump disassembled on the shop table, the damage is seen on the blade tips at the OD of the impeller, and just behind the cutwater on the internal volute wall.

For a 13″ impeller, the free space should be 4% of the impeller diameter between the blade tips and the cutwater.

$$\mathbf{13'' \times 0.04 = .520''}$$

On a 13″ impeller, there should be at least a half-inch free space between the blade tips as they spin past the pump cutwater.

Air aspiration

Air can be drawn into the piping and pump from diverse forms and different points. Air can enter into the piping when the pump is in vacuum. An example of this is a lift pump. Lift pumps tend to lose their prime and aspirate air into the suction piping and pump.

1. The air can come into the pump through:
   - The pump shaft packing.
   - Valve stem packings on valves in the suction piping.

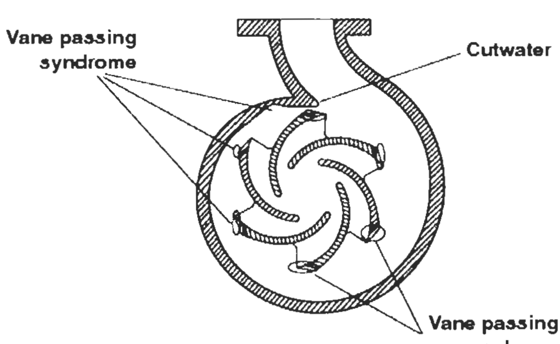

Figure 3–3

- Joint rings on suction piping.
- Flange face sheet gaskets at pipe joints.
- O-rings and threaded fittings on instrumentation in the suction piping.
- O-rings and other secondary seals on single mechanical seals.
- The faces of single mechanical seals.

2. Air can also enter into the pump from bubbles and air pockets in the suction piping.
3. Products that foam can introduce air into the pump.

The evidence of this type of cavitation manifests itself like vaporization cavitation, or inadequate NPSHa. The damage to the impeller appears like vaporization cavitation. **However, the solution is different**.

To prevent this type of cavitation, you need to seal all points of entrance and escape.

1. Tighten all flange faces and gaskets.
2. Tighten all pump packing rings and all valve stem packings on suction piping.
3. Keep the velocity of the fluid in the suction piping at less than 8 ft per second. It may be necessary to increase the diameter of the pipe.
4. Consider using dual mechanical seals with a forced circulation barrier fluid (not induced with a pumping ring) between both sets of faces on:
   - Vertical pumps.
   - Lift pumps and pumps in suction lift conditions.
   - Pumps in vacuum.
   - Pumps operating to the right of their best efficiency point (BEP). This is explained in Chapters 7 and 8.

Turbulence cavitation

This is cavitation due to turbulence caused by the following:

1. Formation of vortexes in the suction flow.
2. Inadequate piping, sharp elbows, restrictions, connections, filters and strainers in the suction.
3. The waterfall effect in suction vessels.
4. Violating or not respecting the submergence laws.

With the pump disassembled on a shop table, the evidence of turbulence cavitation appears like vaporization cavitation or inadequate NPSHa. To deal with these problems, the technician must understand the **'Lost Art of Pipefitting'**. There is a complete discussion on the laws of submergence and turbulence in Chapter 17 of this book.

Review for preventing cavitation

The general rule is

$$NPSHa > NPSHr + 3 \text{ ft}$$

To increase the NPSHa

1. Raise the level in the suction vessel. This increases Hs.
2. Elevate the suction vessel. This increases Hs.
3. Lower the pump. This increases Hs.
4. Reduce the friction in the suction piping. This is probably the most creative way to deal with cavitation. This reduces the **Hf**.
   - Use larger diameter suction pipe.
   - Change the pipe schedule. If there is a designated schedule, you can bet it was based on discharge pressures and not suction pressures.
   - Change to pipe with lower friction characteristics. Ex. Change cast iron piping for PVC or even food grade stainless.
   - Move the pump closer to the suction vessel.
   - Convert globe valves into gate valves if possible.
   - Convert quarter turn butterfly valves into ball valves.
   - Be sure all ball valves are full port design.
   - Be sure all suction valves are totally open.
   - Reduce multiple elbows. If a system is designed with 9 or more elbows in the suction piping, you can be sure that some of these elbows are self-canceling. If so, then some elbows can be eliminated.
   - Convert 2 or 3 close fitting elbows into a flexible 'S'.
   - Convert 'mitered 90° elbows' and short radius elbows into long radius elbows.
   - Keep suction pipe inside diameters clean and scale free.

- Change filters and strainers with more frequency.
- Be sure all pipe gaskets and ring seals are perfectly centered within the flange faces.

5. Lower the temperature of the fluid in the suction vessel. This decreases the Hvp.
6. Pressurize the suction vessel. This increases the artificial **Ha** 23 ft for every 10 psi.

To Reduce the pump's NPSHr

1. Use a pump with a larger suction flange. This lowers the **Hi**. An example of this would be to change a 3 × 4 × 10 pump into a 4 × 6 × 10 pump. The 10-inch impeller needs to remain the same for discharge pressure. However, by converting the 4-inch suction flange into a 6-inch suction flange, the inlet losses would be reduced.
2. Machine and polish the suction throat of the pump. This is probably the worst casting, and roughest finish in the entire pump. Center the suction flange on a lathe and ream-out the suction throat. This reduces the **Hi**.
3. Machine open and increase the inside diameter of the eye of enclosed impellers. This reduces the **Hi**.
4. Use a larger/slower pump. This reduces the **Hi** and **Hf**.
5. Use a small booster pump to feed the principle pump. This increases the artificial head (**Ha**).
6. Use smaller capacity pumps in parallel. This reduces the **Hi** and **Hf**.
7. Use a double suction impeller. Convert an end suction centrifugal pump into a split case horizontal design.
8. Use an impeller inducer.

As you can see by reading through some of these solutions to cavitation, some of the changes are very practical, and others are not.

AUTHOR'S NOTE

A few of the above-mentioned solutions to cavitation are almost comical and not even cost effective. The idea is that they would work to reduce and stop cavitation and the resulting seal, bearing and pump failure. Too many maintenance people (engineers and mechanics) are running around in circles, wringing their hands, and jumping up and down, trying to deal with cavitation. Who would have thought that there are so many solutions, practical or not?

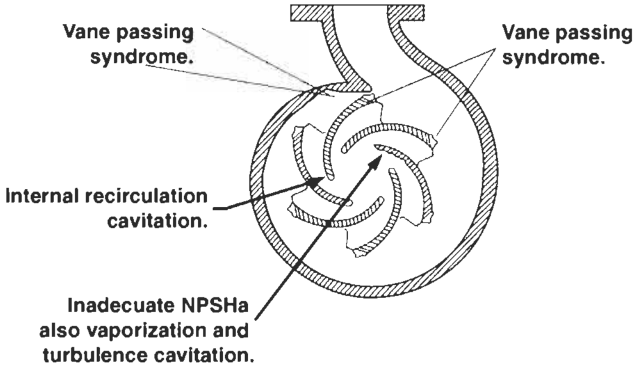

Figure 3–4

Figure 3–4 shows the inside of the pump where cavitation occurs.

Cavitation review

Reviewing the cavitation theme, we observe that the majority of cavitation is caused or induced by operation and design.

As we've discussed, system design is responsible for much of cavitation. Yet, the maintenance mechanic is responsible for stopping and preventing cavitation. And certainly, it's the maintenance mechanic who has to deal with the results of cavitation, the constant changing of bearings, mechanical seals, damaged impellers, wear rings and other pump parts.

Most mechanics have seen the damaged pump parts with the pump torn apart on the shop table. Almost all mechanics have seen the scratches, gouges, and track marks of cavitation on the impeller blades and pump housings. But without understanding and analyzing the causes of cavitation damage, the mechanic can only install more bearings and seals, and possibly hide the damage by re-metalizing the housing and impeller. This is somewhat frustrating for the mechanic, because he or she will be performing the same repair work in the next few weeks or months.

Do something about cavitation!!

The worst thing you can do is....nothing. Do something. Take this information, go back into your process plant, and you can prevent and stop the majority of cavitation.

Type	Cause	Explanation
Vaporization	Operation / Design	Vaporization (inadequate NPSHa) is the result of something that happens in the suction side of the pump, strangled valve, clogged filter, inadequate submergence.
Internal Re-circulation	Operation / Design / Maintenance	Internal Re-circulation results from something in the discharge side of the pump: strangled valve, clogged filter, over-pressurized header, check-valve installed backwards.
Vane Pass Syndrome	Design / Maintenance	Oversized impeller, inadequate aftermarket parts, repair or rebuild with incorrect specifications and measurements.
Air Aspiration	Design / Operation / Maintenance	Design, Improper suction pipe, fluid flow too fast. Inadequate flange torque, operation to the right of BEP.
Turbulence	Design	Design, Inappropriate suction system (vessel, piping, connections, fittings) design.

Be aware that in some cases, you'll have to live with cavitation. Many pumps suffer cavitation for reasons of inadequate design. For example, when operating only one pump in a parallel system, this pump tends to go into cavitation. Pumps that perform more than one duty through a valve manifold tend to suffer cavitation. Pumps that fill and drain tanks from the bottom tend to suffer cavitation. The last pump drawing on a suction header tends to cavitate. And of course vacuum pumps and pumps in a high suction lift are candidates for cavitation.

Some solutions may not be practical, or economical, or timely and consistent with production. You could be forced to live with cavitation until the next plant shutdown to make the necessary corrections. In the meantime, the cavitation shock waves and vibrations will travel through the impeller, down the shaft to the mechanical seal faces, and onto the shaft bearings. We offer some specific recommendations for surviving cavitation shock waves and vibrations in Chapters 13 and 14 on Mechanical Seals.