SEVERE SUCTION BELL DAMAGE IN LARGE, OPEN IMPELLER, VERTICAL TURBINE PUMPS

by
Michael D. Smith
Pump Consultant
Dupont Company
Wilmington, Delaware

Michael D. Smith is a Pump Consultant for DuPont Engineering, in Wilmington, Delaware. He works with design, maintenance, operation groups, and with pump suppliers to minimize DuPont's total cost for moving liquids.

Mr. Smith has a B.S. degree (Mechanical Engineering) from the University of Michigan (1977) and is a registered Professional Engineer in the State of Delaware. He is an active participant in standards activity (Hydraulic Institute User Canvass, ANSI/ASME B73, Process Industry Practices Pump Practice Reviews).

ABSTRACT

Sixteen (nine 1500 hp and seven 500 hp) single stage, vertical turbine, cooling water pumps suffered massive metal loss within two years of installation. All pumps had cast iron suction bells and semiopen, manganese bronze impellers. An accounting of the conditions that resulted in the perforation of the 2 in thick suction bells (one suction bell separated from the pump and fell to the bottom of the pit), including photographs, is given in this case history. Conclusions on how the damage occurred are given and other theories are considered.

A description of the modifications to the pumps is given, as are the results of followup inspections showing only normal wear. The large pumps were converted to enclosed impeller designs, but retained cast iron as the suction bell material. The smaller pumps still have open impellers, but the suction bells have been fitted with aluminum bronze inserts. This case history is given to show that current industry practice for general purpose (not utility class) water pumps is not adequate for larger size pumps.

INTRODUCTION

The System

A large chemical plant has used bronze fitted, cast iron, vertical turbine pumps to circulate cooling water for over 30 years. In 1994, a new cooling water system (Figure 1), including new pumps with semiopen impellers (Figure 2), was installed and began operation. Nine 1500 hp pumps draw water from a large cooling basin. The water is supplied, under pressure, to thousands of points in the plant for process cooling. It then flows back toward the basin in an open canal. Seven 500 hp pumps then lift the water to the top of a cooling tower, where it is cooled before returning to the basin.

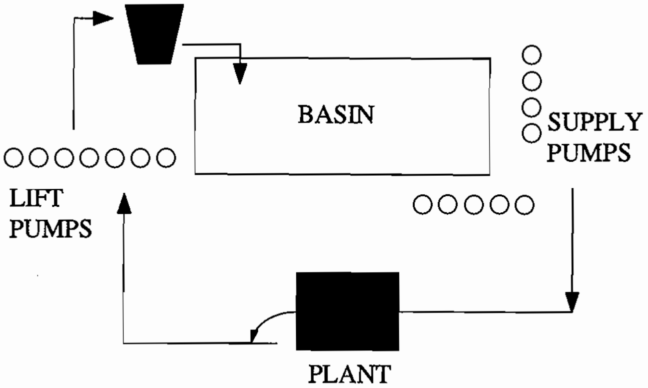

Figure 1. Cooling Water System.

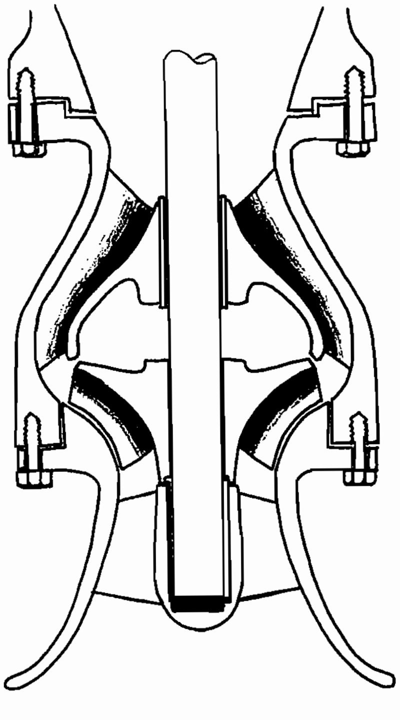

Figure 2. Vertical Turbine Pump with Semiopen Impeller.

The Problem

Nine 1500 hp single stage, vertical turbine, cooling water pumps suffered massive suction bell metal loss within 5000 operating hours (Figure 3). The same problem was observed, to a lesser extent, on seven 500 hp pumps in the same system. It took over 13,000 operating hours to reach the same level of damage as the larger pumps. Plant production depends on the availability of cooling water, and the discovery of the damage caused great concern because it was assumed to involve all 16 pumps. Short and long term solutions were being developed even before the full extent of the damage was known.

INVESTIGATION

The first indication of a problem with the suction bell material was on November 6, 1994, when one of the 1500 hp supply pumps

Figure 3. Metal Loss Resulted in the Penetration of this 42 Inch Supply Pump Suction Bell.

was removed for inspection. While the pump was apart for other work, a localized loss of metal was discovered on the suction bell in the area swept by the first third of the impeller vanes. The affected area was less than 3.0 in across, but had one pocket over 0.25 in deep (Figure 4). The belief at the time was that normal wear had uncovered a casting defect, and the supplier agreed to provide a free replacement bell.

Figure 4. Early Suction Bell Damage Is Localized.

On July 24, 1995, one of the 500 hp lift pumps was removed to repair another problem, and its suction bell was found to have a more generalized attack, similar to Figure 5, within the vane-swept area. Again, the diagnosis of the damage cause was incorrect. In this case, it was assumed that two brief cooling water pH excursions, recorded in February and June of 1995, were responsible for the damage.

Finally, on September 13, 1995, inspection of another supply pump, removed because of high vibration, lead to the realization that a major problem existed. Although the rest of the pump looked fine, the suction bell had suffered extensive, through-section, metal loss (Figure 6). The total area of the suction bell perforations was in excess of 1.0 sq ft, so the pump had probably not been a positive contributor to cooling system flow for some time prior to that date.

The next pump to be removed was selected by examining vibration readings and operating time records for the other supply pumps. The pump selected had the most operating hours and had high vibration. It was removed on September 20, 1995, and was missing all of the suction bell below the flange. A splash was heard during pump removal, and it is assumed that the bell fell off while the pump was being lifted.

After temporary repairs were made to these two supply pumps, they were reinstalled, and the supply pump with the lowest operating time was removed to confirm that the degree of damage was related to operating time. The suction bell was damaged, but the pockets were less than 0.5 in deep. This confirmed that damage was related to operating time (not exposure time), and that the pH excursions were not a major contributor (this pump was not in operation during either excursion).

Figure 5. Late First Stage Damage.

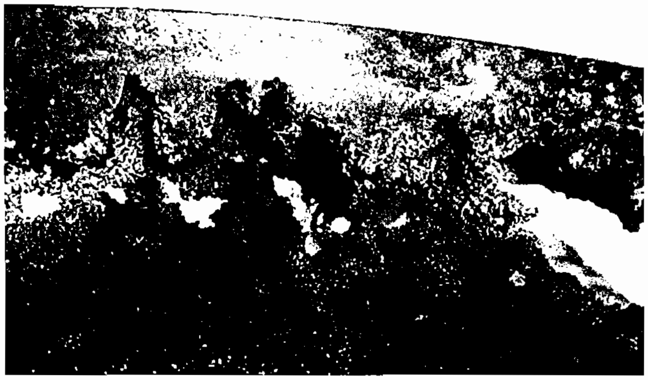

Figure 6. Late Second Stage Damage.

MODIFICATIONS

Since the rate of metal loss was too high to be tolerable, and it did not appear to be due to any change in the cooling water chemistry, both groups of pumps had to be modified. The lift pumps were in the first stage of suction bell damage at the time (October 1995) the long term plan was developed. Since the suction bells were largely intact, the least expensive solution was fitting them with nickel-aluminum bronze inserts. The inserts were designed to be held in place by the clamping force of the suction bell-to-bowl flange and to extend beyond the vane-swept area. In this way, all possible bubble collapse sites have a surface much more resistant to damage.

The larger supply pumps had suffered much greater metal loss than the lift pumps, so there was no way to repair the suction bells or fit them with inserts. Also, there was concern that even the nickel-aluminum bronze might not be satisfactory in this service, given the inability of manganese bronze impellers to maintain an oxide layer (Figure 7). The long term solution was to convert the supply pumps to enclosed impellers. This allowed the new suction bells to be made from cast iron, since they would not be exposed to rising pressure. The new impellers contain all bubble collapse activity and are made of 316 SS, which was expected to be more than adequate for long life in these conditions.

Because of the number and size of the pumps involved, there was a significant amount of interest in how successful these

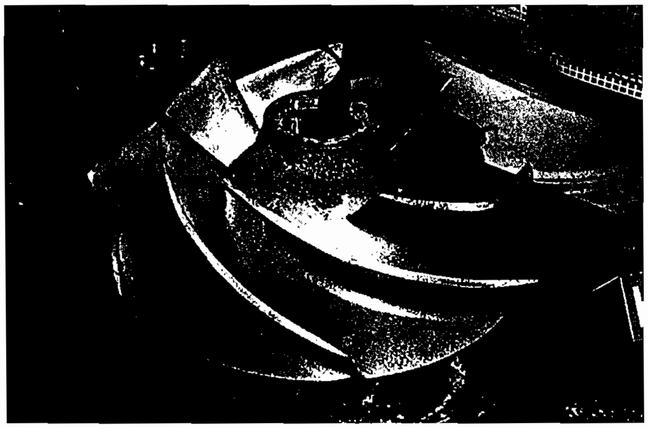

Figure 7. Supply Pump Impeller Has Developed a Dark Oxide Layer Only in the Hub Area.

modifications are. The first inspections of modified pumps were made in September 1996. One lift pump and one supply pump, each with about 5,000 hours of actual run time, were pulled and had their suction bells removed for inspection. Both pumps were in excellent condition. Neither the bronze insert in the lift pump nor the cast iron wear ring surface of the supply pump had any significant loss of metal.

DAMAGE THEORIES

By October 10, 1995, a number of theories had been developed for how the damage occurred:

Cavitation

Cavitation is always present in this application. With the NPSH margin at 35 percent of $NPSH_R$, the amount of cavitation may be small, but most sources indicate that a margin in excess of 100 percent is needed to eliminate cavitation. This theory would predict damage in the first third of the vane swept area.

Vane Tip Turbulence

While this damage theory involves vaporization, it is not at the same place in the pump where cavitation would be found. When a vortex formed at a vane tip is intense enough, the pressure can fall below vapor pressure at its center. As the vortex dissipates, the vapor bubble collapses. The highest vane tip speeds are at the discharge end of the vanes. This is also where the highest tip leakage can be generated (the pressure difference from one side of the vane to the other can be much higher at the discharge end than at the suction end). This theory would predict damage in the middle to last third of the vane swept area.

Erosion/Corrosion

The pump manufacturer felt the cooling water was unusually corrosive. If true, or if there were abrasives present, it would certainly lead to accelerated metal loss.

Operating Point

If the pumps were operated above the rated flow capacity, $NPSH_R$ would increase and cause an increase in cavitation. High flowrates could occur if parallel pumps did not share the demand equally, or if total demand were too high.

Sump Design

Turbulence, vortexing, and gas entrainment can be caused by inadequate sump design. This theory would predict that pump location could be related to the rate of damage.

Impeller Clearance

The rotor "lift" setting is critical to suction performance. In addition to cavitation, excessive vane to suction bell clearance can cause loss of head performance that can cause low flowrates when the pump is operated in parallel with other pumps. This theory would predict that some pumps would have more damage than others (unless all were set wrong).

Each damage theory was tested for validity with the available evidence.

EVIDENCE

Cavitation

The suction bell damage looks like cavitation damage, but it is hard to imagine how vapor bubbles created in the impeller eye would preferentially cause damage at the bottom of pockets in the suction bell over one inch deep (Figure 6). Much of the surface area of the bronze impellers is clean and free from any visible oxide layer (Figure 7). This tends to confirm that some amount of cavitation is occurring, but conventional cavitation is not likely to be the sole cause of metal loss in these pumps. The pump performance details are given in Table 1.

Table 1. Design Pump Performance.

Pump	Motor HP	Rated TDH (ft)	Rated Flow (gpm)	$NPSH_R$	$NPSH_A$
Supply	1500	181.5	24,000	31.3	42
Lift	500	68	20,833	26	32

Vane Tip Turbulence

The second stage damage did occur in the middle of the vane swept area, and the 1500 hp pumps do have a higher vane tip speed than the 500 hp pumps. While this damage mechanism may have been present, it does not explain the deep pockets. There is no reason to expect the bubble collapse from vane tip turbulence to occur preferentially at the bottom of the pockets.

Erosion/Corrosion

No evidence of an unusually high level of abrasives was found. Corrosion always plays a role in metal loss, whether due to erosion (oxidizing the newly exposed surface) or surface fatigue (corrosion lowers the endurance limit). There are several variables that impact how "aggressive" water is to cast iron. Temperature (Figure 8), pH (Figure 9), conductivity (Figure 10), residual chlorine (Figure 11), and total chlorides (Figure 12) were recorded throughout the life of the damaged pumps. While the two periods of low pH are suspicious, one supply and one lift pump were not in service during either period and accumulated the same damage as the other pumps. This indicates that the periods of low pH did not have a measurable impact.

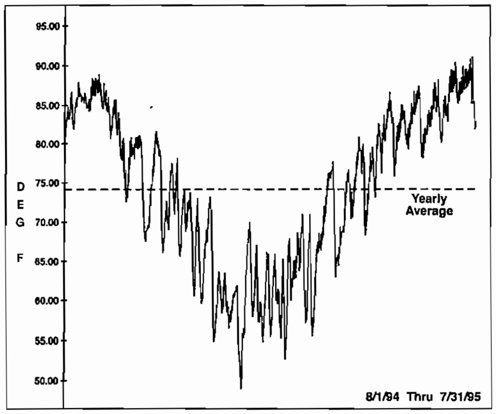

Figure 8. Cooling Water Temperature During the First Year of Pump Operation.

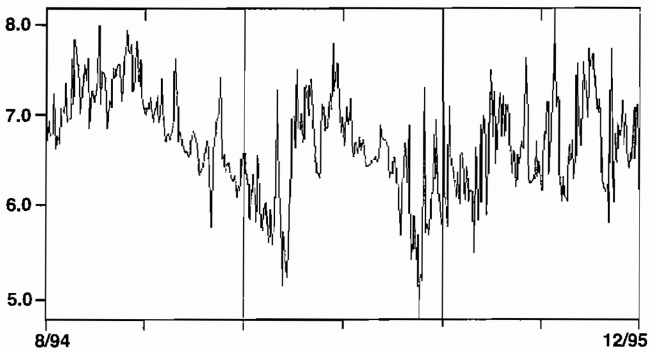

Figure 9. Cooling Water PH During First 17 Months of Operation.

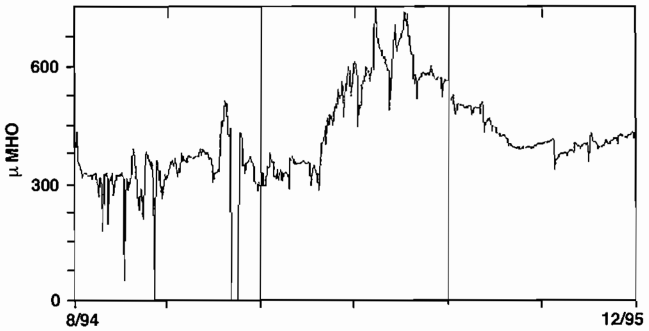

Figure 10. Cooling Water Conductivity.

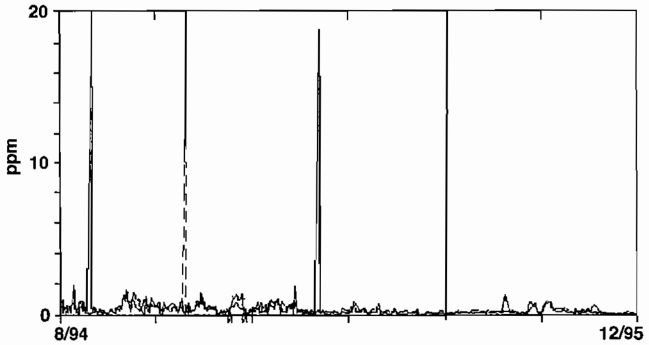

Figure 11. Cooling Water Excess Chlorine.

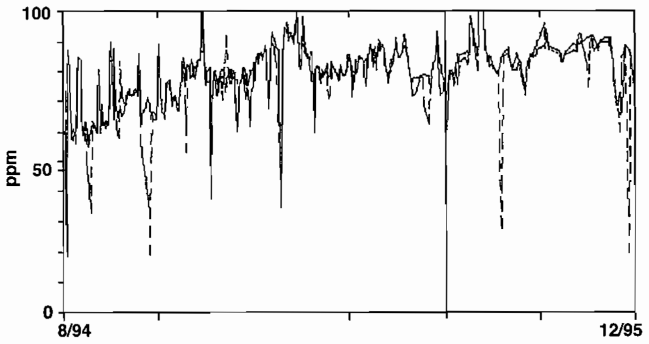

Figure 12. Cooling Water Total Chlorides.

Additional measurements of residual chlorine near the addition points in the supply pump pits indicated some lack of mixing. This can lead to potentially damaging levels of low pH. This was also found to be insignificant since the lift pumps are not near the addition points and had similar damage.

Operating Point

The plant cooling water system flowrates were also recorded (Figure 13). There is no pattern of operation above rated capacity and there were no reports from the field of the noise that would certainly occur if pumps of this size were cavitating.

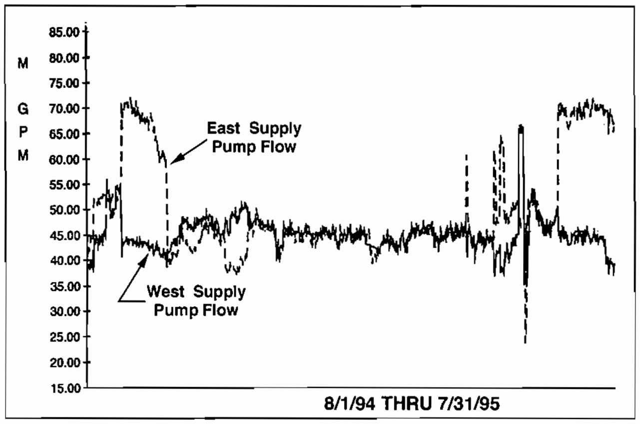

Figure 13. Supply Pump Station Flowrates.

Sump Design

Both the user and the pump supplier agreed that the sump design was quite good and exceeded the requirements of the Hydraulic Institute (Section 1.3.3.4). It is not believed that vortexing or other suction system problems contributed to the damage.

Impeller Clearance

The rotor lift was checked and rechecked, and found to be correct.

CONCLUSIONS

Suction bell damage appears to have occurred in two stages. First, the surface is damaged by the collapse of bubbles formed in the impeller eye. Next, the shallow pockets are made progressively deeper by an unusual type of cavitation, where vapor bubbles are not formed in the impeller, but at the bottom of the pocket.

In the first stage of damage, two types of bubbles are involved. Water vapor bubbles are present due to incipient cavitation. Although there is a significant NPSH margin in this application, it is only a margin from 3 percent head loss, not from the onset of bubble formation. The quantity and size of these bubbles are probably quite small. Air bubbles must also be present, since the water pressure drops below atmospheric pressure as the water accelerates into the impeller eye. Chen (1993) provides a method for calculating the quantity of air that comes out of solution, but the degree of saturation must be known. Assuming complete saturation gives a conservative answer. Surface damage from either type of bubble occurs where the bubbles collapse. This tends to be in the first third of the vane-swept area.

Many of the bubbles collapse without causing damage, but those that collapse near the surface of the impeller or suction bell create very high contact stresses in a very localized area. It is important to keep two things in mind at this point: these high stresses only occur in the bubble collapse region, and the stresses will only cause damage if they exceed the ability of the pump materials to withstand them. Most of the cooling water pumps in chemical plants use enclosed impellers made of bronze. All of the pressure rise takes place inside the impeller and bronze can normally withstand the stresses of bubble collapse. The suction bell sees only regions of falling pressure, and cast iron has worked well. With a semiopen impeller, both the impeller and a portion of the suction bell are in the bubble collapse region. If the suction bell is made of cast iron, it may suffer damage as a result of being exposed to bubble collapse. At the point of bubble collapse, spalling caused by high stress and/or erosion caused by high velocity, remove the oxide layer. The slightly corrosive nature of water containing dissolved oxygen and minerals quickly oxidizes the exposed material.

In the second stage of damage, an unusual type of cavitation causes a more rapid loss of metal. The pockets, formed in the surface of the suction bell during first stage damage, interact with the pressure wave of each passing impeller vane. After the pressure wave reflects off the bottom of the pocket, a very low pressure region is formed. The pressure is low enough, and lasts long enough to cause vaporization. This second stage damage occurs near the bottom of the cavities formed earlier, allowing them to become arbitrarily deep. This damage would tend to be most severe in the middle of the vane-swept area, since the pressure wave would be less intense near the leading and trailing edges of the vanes.

The conclusion that there are two distinct stages of damage is supported by the appearance of the supply pump suction bells (Figure 6). It appears the deep pockets were progressing toward the last third of the vane swept area, even though there is no surface damage in that area.

See "MODIFICATIONS" for a description of how the metal loss problem was resolved.

REFERENCES

Chen, C. C., October 1993, "Cope With Dissolved Gases in Pump Calculations," Chemical Engineering, pp. 106.