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Palo Verde Nuclear Generating Station Cracked Reactor Coolant Pump Shaft Event

by
Howard Maxwell
Consulting Engineer
Arizona Public Service
Phoenix, AZ

Howard Maxwell is a Consulting Engineer for Arizona Public Service at the Palo Verde Nuclear Generating Station. He has been the Station Vibration Engineer for 14 years, and is responsible for the Station Vibration Program. He has been a Vibration Engineer in the Petro-Chemical and Nuclear industries for over 25 years, and has authored over 30 technical papers and presentations. He has a degree in Electrical Engineering from New Mexico State University, is a Registered Professional Engineer, and is certified by the Vibration Institute as a Vibration Specialist II. He is a member of the Board of Directors of the Vibration Institute, a member of the ASME, and serves on several of the ASME O&M Committees including the Subcommittee on Condition Monitoring, and the Subgroup on Rotating Equipment.

HISTORY OF RCP SHAFT CRACKING AT PALO VERDE

In 1987 Palo Verde became aware that several European RCP shafts similar to PVNGS shafts had exhibited shaft cracking. As a result, Palo Verde implemented an inspection program for our shafts which found cracks of varying depths and lengths. None of the cracks had progressed to a point where vibration would have indicated a problem. A comprehensive root cause assessment was implemented, as well as an augmented vibration monitoring program.

After several years all the shafts were changed out to redesigned or modified versions. During this period no failures occurred and no crack became large enough to cause a vibration indication.

PROBLEM DETECTION

First Indicator

Starting on about 3/13/96 - the 1xRPM vibration began trending up from a range of about 0.9-1.7 mils (minimum to maximum).

On Friday 3/28/96, the Unit 1 RCP 2B came into alarm on the 1xRPM acceptance region at 1.5-2.4 mils. The Vibration Technicians responded to the alarm, and about 2 hours before quitting time showed me trend graphs from the installed monitoring system similar to Figures 1 and 2. These graphs do not give a very clear picture of the pump condition for several reasons. First, the graphs are on a fixed scale much larger than the actual values. Second, the time scale is only 3 weeks because the system only stores that much data. As described below, this event had started earlier. In spite of this, there is clearly something going on in the 1xRPM, and perhaps in the 2xRPM. Note that the increase from 3/13/96 was about 0.6 mils on a signal with a noise band of about 0.8 mils. The overall level at this time was 2.69-3.56 mils and had not shown the trend yet. The manufacturer's limits are 8 and 10 mils, so this level of vibration is in the excellent range. The Vibration Technicians began monitoring the pump daily over the weekend.

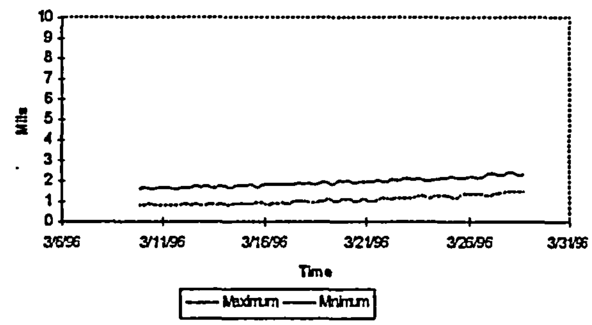

Figure 1. RCP Y-Probe 1xRPM Vibration

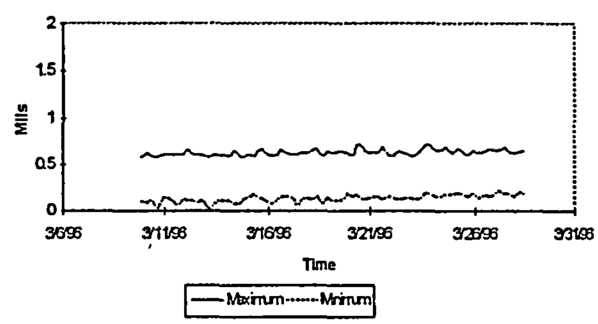

Figure 2. RCP Y-Probe 2xRPM Vibration

We have a long-term trending system, where we take the data from the installed system and enter it into a database. Over the weekend we updated the database with the current data and produced the graphs shown in Figures 3,4,5 and 6. Note that the two curves in Figures 3 and 4 are now the averaged values of both probes, rather than the maximum and minimum of only one probe. Figure 5 shows the polar graph of the Y probe 1xRPM vector; the X probe was identical except for a 90 degree shift. The gap in the data on the four graphs is because we missed collecting data from the installed system for input into the long term-trending system. Note that during this gap something happened. Naturally, Murphy's Law says that any interesting data will somehow go missing. For a couple of days

we thought the pump had been tripped during this period. We usually see 1xRPM changes during a trip, so that change could have been because of a trip, but we had never seen a 2xRPM shift caused by a trip. We found out that the plant had tripped due to a lightning strike, but the pump had not tripped. Clearly something is going on in the pump. The symptoms, except for the lack of a clear 2xRPM phase change, indicate a possible cracked shaft.

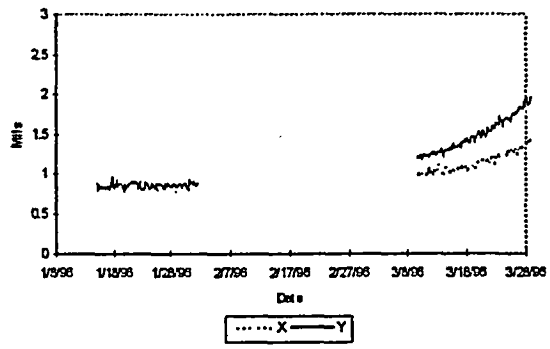

Figure 3. X&Y Probes - 1xRPM Average Vibration

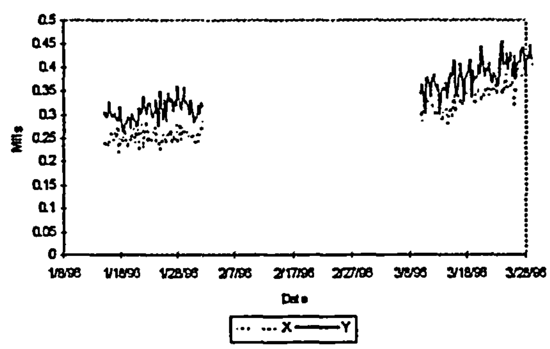

Figure 4. X&Y Probes - 2xRPM Average Vibration

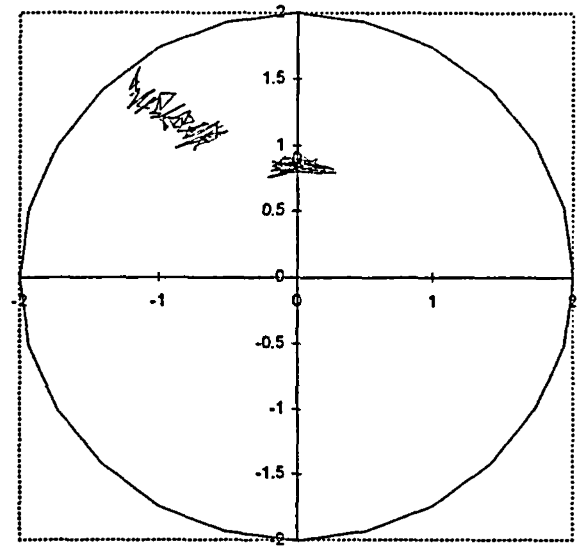

Figure 5. Y Probe Averaged 1xRPM Vector to 3/28/96

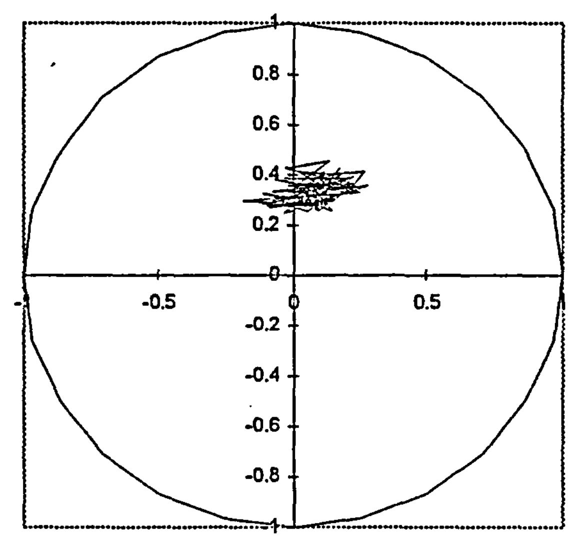

Figure 6. Y Probe Averaged 2xRPM Vector to 3/28/96

MONITORING, EVALUATION, AND PREPARATIONS CONTINUE

The vibration continued to trend up through 3/30/96 at about 10:00 am, when there was a step change down. This step down caused us to question our tentative conclusion of a crack. After all, a crack will not heal itself. However, the vibration trend continued up, and after several days it became apparent that the trend was exponential. The symptoms still indicated the possibility of a cracked shaft, although several other

possibilities existed including cracked bolts in the coupling or other coupling problems. Continued trending would confirm the diagnosis.

On 4/3/96 we estimated the life of the pump, if there was a shaft crack, to be 10 to 30 days until failure, i.e. between 4/13/96 and 5/3/96. This estimate was based on a similar pump in Europe which had developed a crack and had been allowed to progress to failure at 20 mils. As it turned out our crack progressed much more slowly than the European pump.

On 4/4/96 we held the initial meeting to begin to plan for replacing the shaft. Action items included: contact outside vibration experts; begin to plan for possible replacement; verify instruments; and continue to monitor daily, providing daily reports by e-mail to a long list.

On 4/8/96 there was a report on a local TV station news program that mentioned the increasing vibration levels of a Reactor Coolant Pump at Palo Verde.

By 4/10/96 it had become clear that the trend of vibration was much slower than the European experience. We decided that because of some differences between our pump and the European pump, and the difference in the trend, we would use a limit of 10 mils as the point of failure. We also developed a method of extrapolation of the data, which predicted a 10 mil level on 4/21/96.

By 4/12/96 the phase angles began changing noticeably.

On 4/15/96 the updated extrapolation predicted a 10 mil level on 4/18/96.

During the period from 4/4/96 to 4/15/96, maintenance had made considerable progress toward preparing for the pump outage. A plan had been developed, specialized tools were located which were difficult to find because they hadn't been used for 8 years, crews were identified and scheduled, a spare seal housing had been obtained and a new seal pack had been assembled. Maintenance was essentially ready, so on 4/16/96 the pump was shutdown at a level of about 7.5 mils. Figure 7 shows the final trend graph with extrapolations.

There are three extrapolations shown in Figure 7. The first is a straight line fit, which in the early stages matched the trend pretty well. The second is the European failure, adjusted for a different operating speed and shaft size. The third is a fifth order polynomial fit. As the failure progressed, the order of the fit required to match the data increased from third order curve to a fifth order curve. I think that the theoretical curve is a 4.5 order curve. Figures 8, 9, 10, and 11 show the other parameters.

FINAL DATA

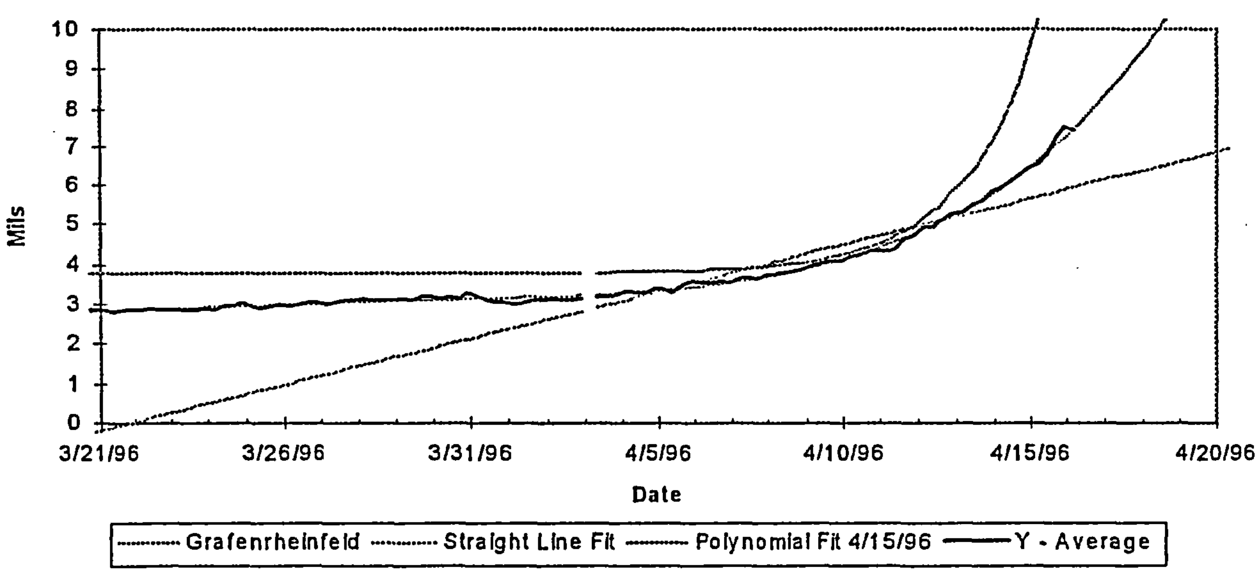

Figure 7. Overall Vibration with Projections

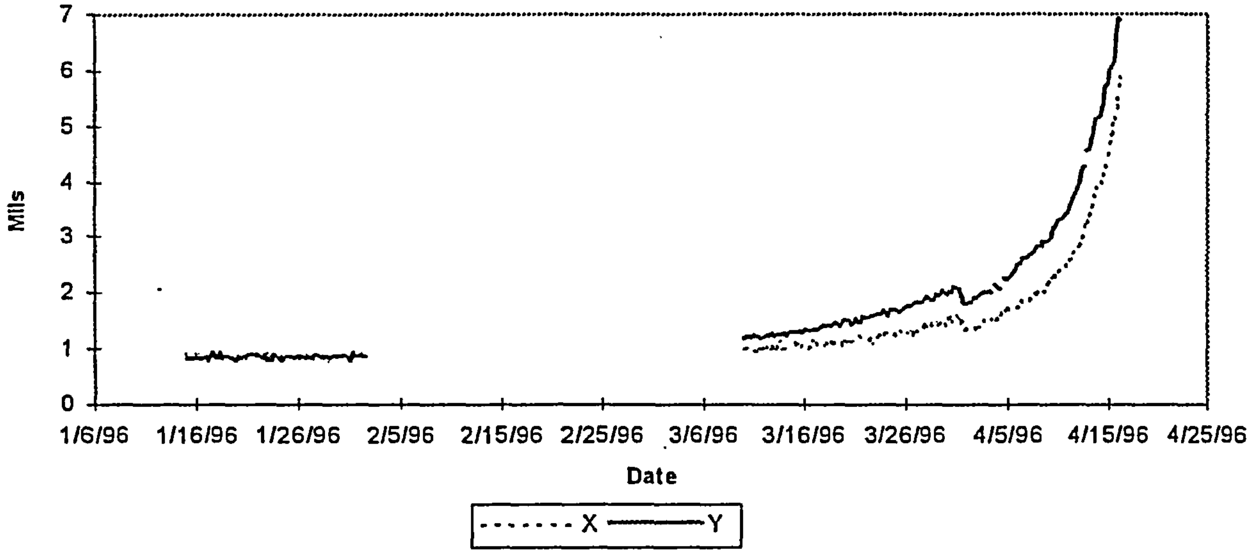

Figure 8. X & Y Probe 1xRPM Vibration

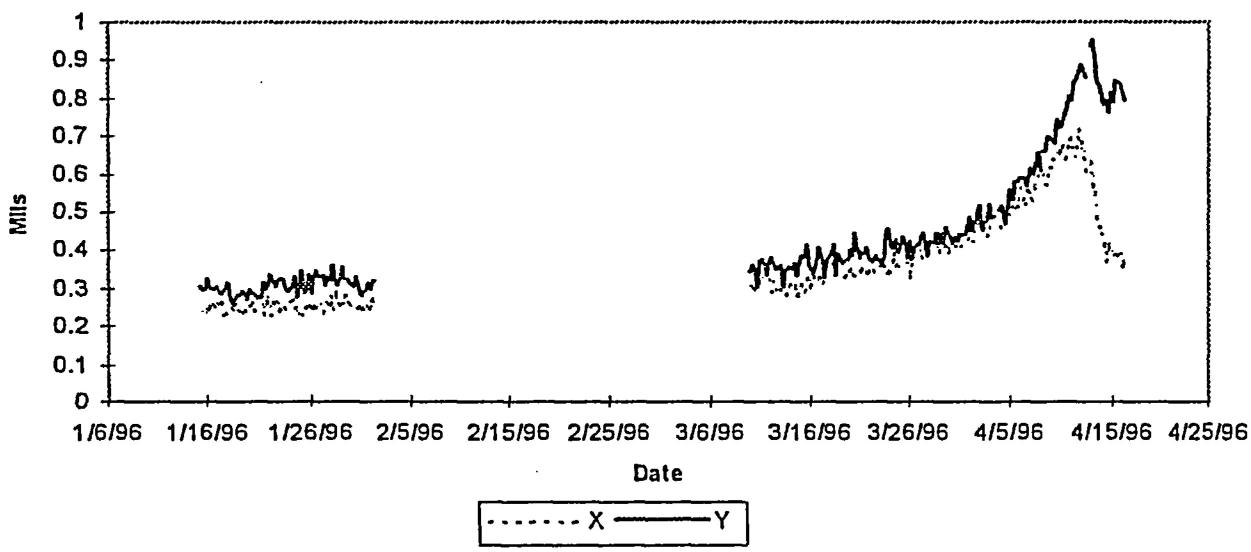

Figure 9. X&Y Probes 2xRPM Vibration

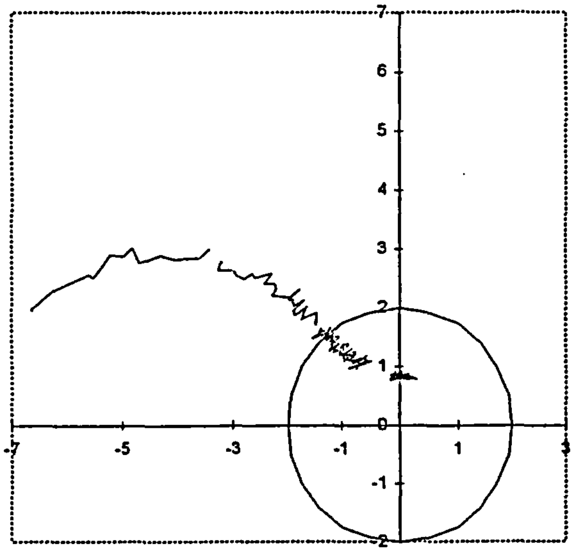

Figure 10. Y Probe 1xRPM Vector

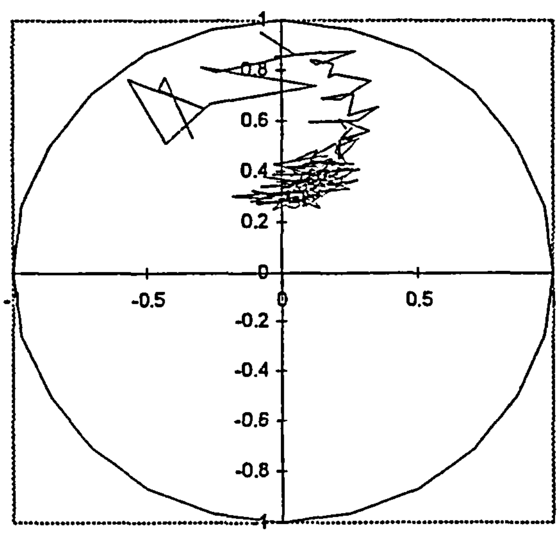

Figure 11. Y Probe 2xRPM Vector

Several features of the data are of interest. First is the drop in vibration on 3/30/96. An inspection of the curve in Figure 8 before and after the drop, shows that the slope of the curve seems to be more linear after the drop than before, and this continues till about 4/12/96. This could be explained by the center bore hole. As the crack encounters the first wall of the hole, the asymmetry of the shaft is changed as the bore hole diameter is added to the crack. Secondly, as the crack progresses around the hole, the change in asymmetry is less than before or after the crack has encountered the bore hole.

The change in slope on 4/12/96 could be when the crack encountered the second wall of the bore hole.

The second interesting feature is that the 2xRPM amplitude never exceeded 1 mil, while the 1xRPM went to near 8 mils. This is contrary to many expectations. Also the 2xRPM vector made almost a complete circle in the polar plane.

REPAIR AND INSPECTION

The pump was shut down and inspection began. There were no problems found with either the flexible coupling between the motor and the thrust bearing assembly, or the fixed coupling between the thrust bearing assembly and the pump lower shaft. The fixed coupling was disassembled and the thrust bearing assembly raised to allow access. The pump shaft has a hole drilled down the center which is used to perform ultrasonic checks for cracks. The access plug was removed and the mechanics looked in the hole with a light. Water was observed rising in the hole. The plug was reinstalled, and the pump rotor removed and replaced. Later ultrasonic testing from the upper end of the shaft confirmed a crack, but was not able to determine the size. As of now, the crack has not been opened up for inspection, but it must be at least deep enough to get to the center bore hole.

The mechanics installed a new rotor and seal. Because the new seal assembly had been built, and some significant changes had been made in the repair plan, the time at hot mid loop was greatly reduced. Because of the excellent preparations made by maintenance, the outage was significantly shorter than planned, with greatly reduced radiation exposure and no injuries. Management approved a savings of 7 days of production, which was directly attributable to the Predictive Maintenance Program.

REFERENCES

1. Maxwell, J.H., "Detecting Cracked Reactor Coolant Pump Shafts with Vibration Monitoring", A.S.M.E. paper 88-PVP-11