UNITED STATES
NUCLEAR REGULATORY COMMISSION
WASHINGTON, D. C. 20555

OFFICE OF NUCLEAR REACTOR REGULATION

SAFETY EVALUATION OF RC PUMP SHAFT CRACKING IN

PALO VERDE UNIT 3

1.0 DESCRIPTION OF ISSUE

Reactor Coolant Pump (RCP) shafts of a design similar to those used at Palo Verde Units 1, 2 and 3, exhibited cracks, and in two instances, subsequently failed in European nuclear plants. As a result, Arizona Nuclear Power Project (ANPP) examined the RCP shafts for Palo Verde Units 1 and 2 at their respective outages in October 1987 and February 1988. Initial ultrasonic tests indicated existence of cracks near the keyways similar in nature to those in the European plants. Subsequent surface examinations, non-destructive examinations, metallographic examinations, fractographic examinations (light optical and scanning electron microscopy), chemistry evaluation, mechanical property measurements and stress analyses were performed to characterize the cracks and to determine the possible root causes.

Both circumferential and axial cracks were observed up to a maximum of 15-17mm in depth in the 200mm diameter shafts after an operation of approximately 18,000 hours. Circumferential cracks continued to grow whereas the axial cracks appeared to be arrested after reaching the low stress region. The following scenario for formation and growth of the cracks and subsequent break of the shaft was presented in the ANPP evaluation report (Ref. 1). Due to stress concentration and/or impacting of the key, cracks develop in the chrome plate around the keyway region of the shaft. The chrome plate has a lower fatigue strength than the base material which is martensitic steel, German DIN standard 1.4313 (nearest U.S. equivalent is ASTM A-182 Grade F6NM). Once the cracks penetrate the chrome plate (0.15mm thick), the stress riser at the interface causes the cracks to propagate to the base metal. Further propagation through the base metal is by a high cycle fatigue mechanism resulting primarily from the low alternating bending stresses induced by the hydraulic action of the pump. The cracks continue growing with the operating time, initially at a slower rate and rapidly before the break.

2.0 CORRECTIVE ACTIONS

As a corrective measure, ANPP installed modified shafts for Units 1 and 2. The following modifications were performed:

a. Chrome plate around the keyway was removed.
b. The stop seal was extended into the cylindrical recess in the impeller hub, and the impeller keys were shortened to accommodate the extended seal
c. Step changes in the shaft diameter were chamfered with adequate radius.

Unit 3 is operating with the original shafts. ANPP proposes to replace these shafts with the modified design at the next refueling outage (March 1989).

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In addition, ANPP implemented a vibration monitoring program for all three units. The vibration amplitude of each shaft is continuously monitored by two transducers orthogonally installed on the bearing above the seal housing (see Ref. 2 for details). A sudden change in the total displacement amplitude as well as the spectral components at single (1 x rotating frequency) and double (2 x rotating frequency) harmonics will be used as a warning to indicate rapid crack growth. In case of such a rapid crack development, ANPP has committed to shut down the plant and/or take appropriate actions as delineated in the following five-point program:

"1. Every four hours, monitor and record the vibration data on each of the reactor coolant pumps.

2. On a daily basis, perform an evaluation of the pump vibration data obtained in 1. above by using an appropriately qualified engineering individual.

3. When one vibration monitor on the reactor coolant pump indicates a vibration level of 8 mils or greater, the Nuclear Regulatory Commission shall be notified within four hours via the Emergency Notification System, and

   In addition, when the vibration on any pump exceeds 8 mils due to a shaft crack or unknown cause, within four hours the affected pump shall have its orbit and spectrums continuously monitored and evaluated by an appropriately qualified individual, and

4. When any one vibration monitor on the reactor coolant pump indicates a vibration level of 10 mils or greater, within one hour, initiate action to place the unit in at least HOT STANDBY within the next six hours, and at least COLD SHUTDOWN within the following 30 hours. In addition the affected pump will be secured after entering Hot Standby (Mode 3), and

5. On a daily basis a spectrum analysis shall be performed on the RCP shaft vibration and shall be evaluated for trends by using an individual qualified in the technique. The evaluation shall consist of comparing the running speed and twice running speed spectral components to limits computed from the baseline vibration. The current method used to set the limit is to compute the lowest of: a) 1.6 times the baseline value; b) the mean plus three standard deviations; c) 2 mils for the 2 x RPM component; or d) 6 mils for the 1 x RPM component. When the amplitude exceeds any limit, further analysis shall be performed. This analysis shall consist of inspecting the amplitude versus time plots for a steadily increasing trend, and a review of the other plant data which might explain the change. If the trend is confirmed to not be caused by plant or pump conditions unrelated to a shaft crack, the trend will be extrapolated manually and/or by computer to predict the time at which the vibration is expected to reach 10 mils. The Unit will be brought to HOT STANDBY per 4. above and the affected pump will be secured at least one week prior to this extrapolated time. After reaching HOT STANDBY, the Unit will proceed to COLD SHUTDOWN within the following thirty hours.

ANPP has completed preliminary engineering of a computerized vibration data collection system to facilitate the PVNGS augmented vibration monitoring program. The system would perform continuous on-line 1 x RPM and 2 x RPM amplitude/phase monitoring and spectrum analysis. Final engineering is scheduled for completion in July 1988."

3.0 EVALUATION OF ANPP ACTIONS

Modifications of the Palo Verde RCP shafts performed by ANPP are a logical approach to stop or at least to reduce the crack formation and growth, and are similar to those implemented in Europe. However, several questions still remain unanswered. For example, crack formation has been attributed to the lower fatigue strength of the chrome plate; but shafts with a very low cycle (e.g., 400 hours of operation time) have indicated crack formation whereas some shafts with much longer operation time did not exhibit any crack. Perhaps, the fitting of the key in the keyway plays a major role.

Although the modified shafts are expected to perform better than the orginal designed shafts, their improvement has not yet been proven. Therefore, it is recommended that the same monitoring program which is in place now, continue until the next outages of Units 1 and 2, at which time the effectiveness of the modifications and the requirement of continuation of the vibration monitoring system should be reevaluated based upon data on crack growth for these modified shafts and for those in Europe.

Regarding the vibration monitoring program, collection of the vibration data and subsequent spectral analysis have been successfully performed in the past in various vibration monitoring tests. Therefore, ANPP's data collection and analysis techniques are based upon a proven technology and should be reliable. However, correlation of this data to crack growth still appears to be a challenge and state-of-the-art technology. Various aspects of this correlation are discussed in the following paragraphs.

3.1 Overall Displacement Amplitude

ANPP has performed a literature search to assess the reliability of the overall displacment data to predict rapid crack growth and eventual failure of the shaft. Extensive crack growth and/or failure of the RCP shaft have been studied for four U.S. plants and two European plants. Pumps similar to Palo Verde's were used in the two European plants. Since turbine shafts operate under similar vibratory conditions where gravity load replaces the internal pressure of the pump, the crack growth and failure history of turbine shafts have also been studied.

It appears that an early stage of crack growth cannot be detected by use of the displacement data alone. Note that for Palo Verde Unit 1, crack formations up to 17mm (8.5% of diameter) went undetected. Experience indicates that crack growth up to 25% to 40% of the diameter may be exceeded before the overall amplitude appreciably increases. A sharp increase in the displacement amplitude occurs one or two days before shaft failure. Therefore, if carefully monitored, the displacement amplitude data can provide an adequate warning for a shutdown before the shaft breaks. A one day delay in detecting the amplitude increase may not allow enough time for a cold shutdown.

3.2 Spectral Amplitude

Recent research efforts indicate that the spectral amplitudes of (1 x rotating frequency) and (2 x rotating frequency) components are more sensitive to crack growth and can provide an earlier warning than what displacement amplitude would. The crack causes the stiffness of the shaft to vary with its instantaneous position as the imposed bending moment due to the internal pressure causes the crack to open or remain closed. In the open position, the crack introduces stiffness asymmetry in the two lateral directions. These nonlinearities lead to the appearance of new vibrational components (i.e. 1x, 2x, etc.) at frequencies which are harmonics of the shaft rotational frequency.

The 1 x and 2 x responses are of special interest since changes in higher harmonics are negligible for relatively shallow cracks. When the crack is located near the midspan of the shaft or when it is relatively deep, the effect of flexibility is predominent compared to the effect of asymmetry, and the change in 1 x response is proportionally greater than the change in 2 x response. On the other hand, when the crack is located near a coupling or bearing, or if the crack is relatively shallow, the effect of asymmetry becomes predominant, and the change in 2 x response indicates a greater sensitivity. Since in the Palo Verde RCP the cracks are typically formed near the tip of the key area (i.e. close to a bearing above the impeller), the trend of the 2 x response is expected to provide a clear indication of crack growth at a crack depth of 10% - 20 % of the diameter. At about 35% - 40% crack depth, the 1 x response will also indicate a trend.

3.3 Orbit

At an early stage of crack growth, the filtered orbit is expected to display a smaller circle inside and touching a larger circle. For an advanced crack the orbit may take a crescent shape. The identification and significance of orbital changes and their sensitivity to various types of cracks are part of an evolving technology.

4.0 CONCLUSIONS AND RECOMMENDATIONS

Since Unit 3 pumps will have operated for approximately 15,000 hours before its next outage compared to 18,000 hours or so operating time of the Units 1 and 2 pumps, the performance of the Unit 3 pump shafts is expected to be similar to that of the other units (i.e., any cracks should not grow more than 10% of the diameter). The vibration monitoring should continue for all three units; the course of action on the RCP shafts will depend on how, if at all, cracks develop and grow in the modified shafts.

The staff also recommends that the temporary Bently/Nevada monitoring system be made permanent in order to increase efficiency of the data analysis.

5.0 REFERENCES

1. ANPP Report submitted on May 20, 1988, letter No. 161-01038-EEVB/JRP

2. BNL Evaluation Report submitted on December 2, 1987

3. Nuclear Administrative Technical Manual, PVNGS Reactor Coolant Pump Vibration Monitoring 70AC-0SV08, dated October 28, 1988

Principal contributor: S. Hou

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Mr. Donald B. Karner
Arizona Nuclear Power Project
Executive Vice President
Post Office Box 52034
Phoenix, Arizona 85072-2034

SUBJECT: ARIZONA PUBLIC SERVICE COMPANY, ET AL
PALO VERDE NUCLEAR GENERATING STATION, UNITS 1, 2 AND 3

The following documents concerning our review of the subject facility are transmitted for your information.

- [ ] Notice of Receipt of Application, dated ________.
- [ ] Draft/Final Environmental Statement, dated ________.
- [ ] Notice of Availability of Draft/Final Environmental Statement, dated ________.
- [ ] Safety Evaluation Report, or Supplement No.________ dated ________.
- [ ] Environmental Assessment and Finding of No Significant Impact, dated ________.
- [ ] Notice of Consideration of Issuance of Facility Operating License or Amendment to Facility Operating License, dated ________.
- [X] Bi-Weekly Notice; Applications and Amendments to Operating Licenses Involving No Significant Hazards Considerations, dated 11/16/88 [*see page(s)*] 46166.
- [ ] Exemption, dated ________.
- [ ] Construction Permit No. CPPR-________, Amendment No. ________ dated ________.
- [ ] Facility Operating License No. ________, Amendment No. ________ dated ________.
- [ ] Order Extending Construction Completion Date, dated ________.
- [ ] Monthly Operating Report for ________ transmitted by letter dated ________.
- [ ] Annual/Semi-Annual Report- ________ ________ transmitted by letter dated ________.

Office of Nuclear Reactor Regulation

Enclosures:
As stated

cc: See next page

OFFICE	DRSP/PD5						
SURNAME	JLee						
DATE	12/2/88						

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