FAILURE ANALYSIS OF A REACTOR POOL COOLING PUMP USING MODAL AND VIBRATION ANALYSIS

Thomas J. Hazelwood, Larry D. Phillips, and Blake W. Van Hoy

Oak Ridge National Laboratory

1 Bethel Valley Road

Oak Ridge, TN 37831

Telephone: (865) 576-0340

vanhoybw@ornl.gov

Abstract: Two 75 HP pumps redundantly supply cooling water to the reactor pool of the High Flux Isotope Reactor (HFIR) at the Oak Ridge National Laboratory (ORNL). Due to a recent history of premature bearing failures, one of these pumps has undergone maintenance to deal with possible issues of misalignment and base looseness. Vibration analysis and modal analysis including steady state spectrum, operational deflection shape, run up and down order tracking, and modal impact have been utilized to verify the effectiveness of the maintenance and identify possible remaining failure modes. The studies conclude that the pump is, after the maintenance, in an overall good conditional state as per ISO 10816, but a few failure modes remain. These modes consist of some shaft unbalance, considerable shaft misalignment intensified by piping movement, possible motor ground fault, hydrodynamic issues such as cavitation with modal interaction, and base looseness. These failure modes and their supporting data have been used to make suggestions for future maintenance, to verify the effectiveness of the previous maintenance, and to provide a base on which to check future data. This report will cover the testing setup, methodology, analysis results, and maintenance suggestions.

Keywords: Condition monitoring; diagnostics; failure prevention; fault analysis; signal analysis

Introduction: Two 75 HP pumps redundantly supply cooling water to the reactor pool of the High Flux Isotope Reactor (HFIR) at the Oak Ridge National Laboratory (ORNL). One of these pumps, referred to as PU-9A, has a history of premature bearing failures; therefore, it has undergone maintenance. The bearing failures were thought to be produced by shaft misalignment and base looseness. These issues were addressed during the maintenance. The purpose of the testing summarized in this report is to evaluate the effectiveness of the maintenance and to diagnose any remaining failure modes. The data acquisition equipment and sensor locations will be denoted. The vibration analysis and modal analysis included as part of this report are steady state spectrum, steady state operational deflection shape, run up waterfall, run down waterfall, stationary spectrum, and modal impact tests. The results of these tests will be summarized and used to provide suggestions for future pump maintenance.

Testing Setup: A laptop with commercial data acquisition and analysis software was used to acquire the data, post process the data, and display the results. The results include spectrum charts, waterfall graphs, operational deflection shape videos, modal shape videos, and time data audio clips. Four commercial, 8 input/2 output channel data acquisition hardware units were used in conjunction with the software (See 'Figure 1').

Figure 1: Data Acquisition Hardware

Twenty-five simultaneous channels of accelerometers were epoxied to the pump, motor, base, and piping. The outboard motor and outboard pump both received horizontal, vertical, and axial accelerometers (See ‘Figure 2’ and ‘Figure 3’).

Figure 2: Outboard Motor Accelerometers

Figure 3: Outboard Pump Accelerometers

The inboard motor and inboard pump both received horizontal and vertical accelerometers (See ‘Figure 4’ and ‘Figure 5’).

Figure 4: Inboard Motor Accelerometers

Figure 5: Inboard Pump Accelerometers

The base received six vertical accelerometers on and between the mounting bolts (See 'Figure 6' and 'Figure 7').

Figure 6: Base Bolt Accelerometers

Figure 7: Base Between Bolts Accelerometers

The suction pipe flange, suction mid-pipe, and discharge elbow each received a triaxial accelerometer (See 'Figure 8', 'Figure 9', and 'Figure 10').

Figure 8: Suction Flange Accelerometer

Figure 9: Suction Mid-Pipe Accelerometer

Figure 10: Discharge Elbow Accelerometer

Steady State Spectrum: The steady state spectrum data set consists of several minutes of time waveform data. The data was sectioned into blocks and each block was transformed into the frequency domain using the Fast Fourier Transform (FFT). Each FFT was then averaged into a single set of spectrum data. This process was repeated for each accelerometer. Significant and representative data will be displayed and discussed within this report. It is important to note that the run speed of the motor is 59.3 Hz. One and two times run speed (1x and 2x) peaks with harmonics show up in the motor's spectrum (See 'Figure 11" and 'Figure 12').

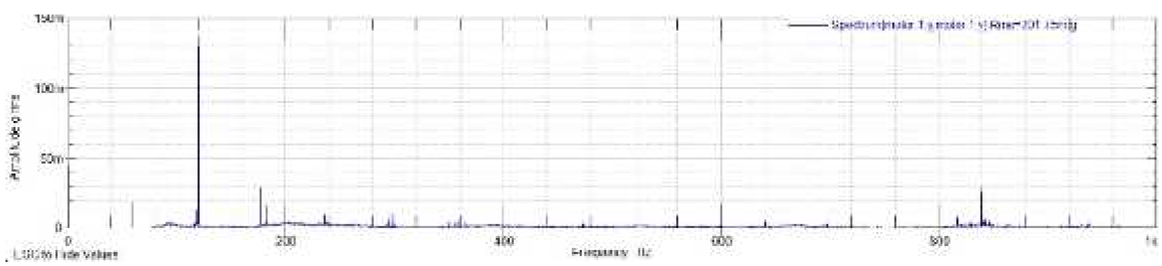

Figure 11: Steady State Outboard Motor Spectrum (Horizontal Radial)

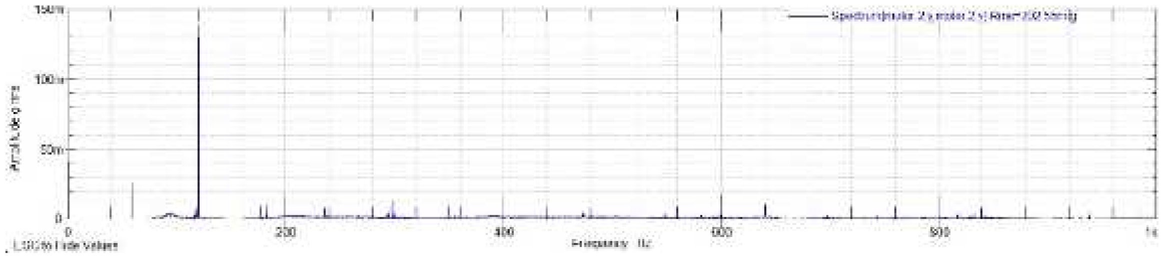

Figure 12: Steady State Inboard Motor Spectrum (Horizontal Radial)

One and two times run speed peaks with harmonics also show up in the pump's spectrum with the addition of broadband noise (See 'Figure 13" and 'Figure 14'). Also, note the twin peak in 'Figure 13' around 720 Hz, as this will be discussed in the Modal Impact section.

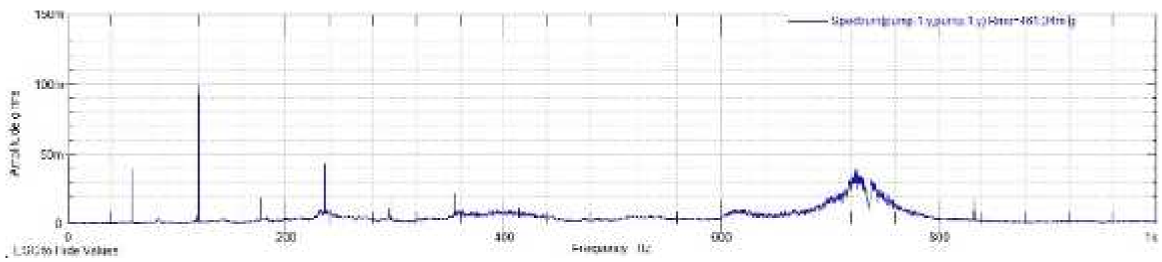

Figure 13: Steady State Inboard Pump Spectrum (Horizontal Radial)

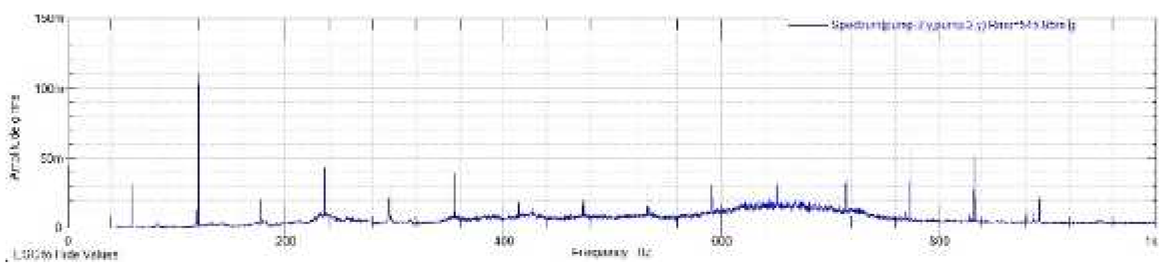

Figure 14: Steady State Outboard Pump Spectrum (Horizontal Radial)

The 1x vibration is indicative of some shaft unbalance, but it is much lower than the 2x vibration which is indicative of shaft misalignment. Care needs to be taken analyzing the

2x vibration in separating the two times run speed (118.6Hz) from two times the line frequency (120Hz). The bearing frequencies can be seen but are not significantly higher that the noise floor. This should be expected since they have recently been replaced. The broadband noise of the pump is indicative of hydrodynamic effects such as cavitation. Audio files of the pump and motor along with impulses within the time domain back up the impression of cavitation.

Steady State Operational Deflection Shape (ODS): Magnitude and phase data as a function of time from each accelerometer is combined with a simple representation of the system geometry to illustrate the operational deflection shape. The first ODS of interest, seen in 'Figure 15', utilizes the spectrum data from 1x the run speed. All deflections are scaled to the largest motion, which is 1 mil peak-peak of the discharge elbow. The dotted lines represent the non-deformed geometry. The shaft and the base have a relatively small deflection at this frequency.

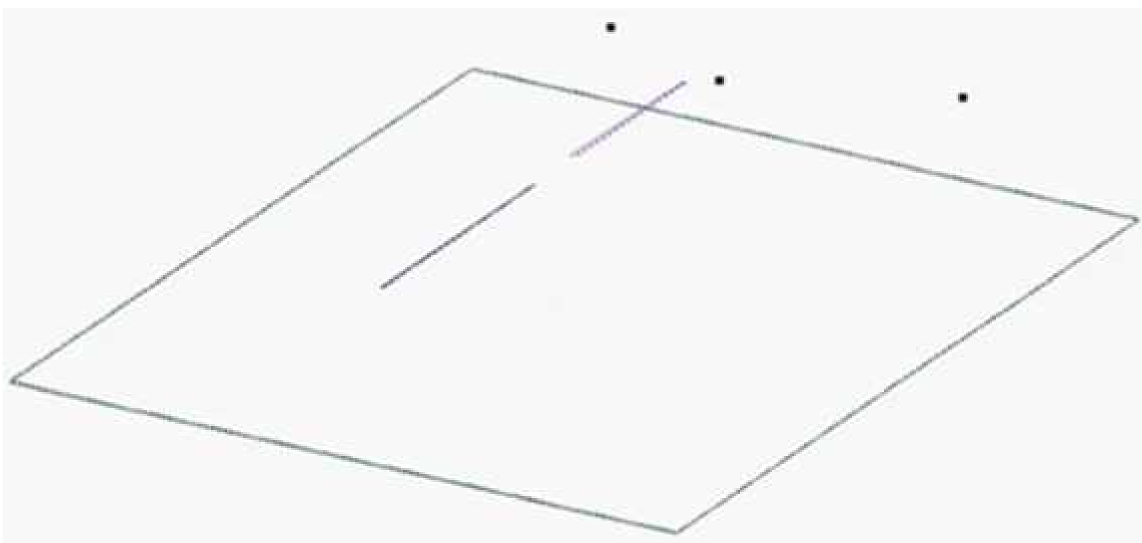

Figure 15: 1x Run Speed ODS

The Second ODS of interest, seen in ‘Figure 16’, utilizes the spectrum data from 2x the run speed. All deflections are scaled to the largest motion, which is 1 mil peak-peak of the suction mid pipe. There is high deflection of the shaft that also transfers to the base. A 2x run speed vibration of the shaft is often due to misalignment of the shaft, which the movement of the pipes can amplify.

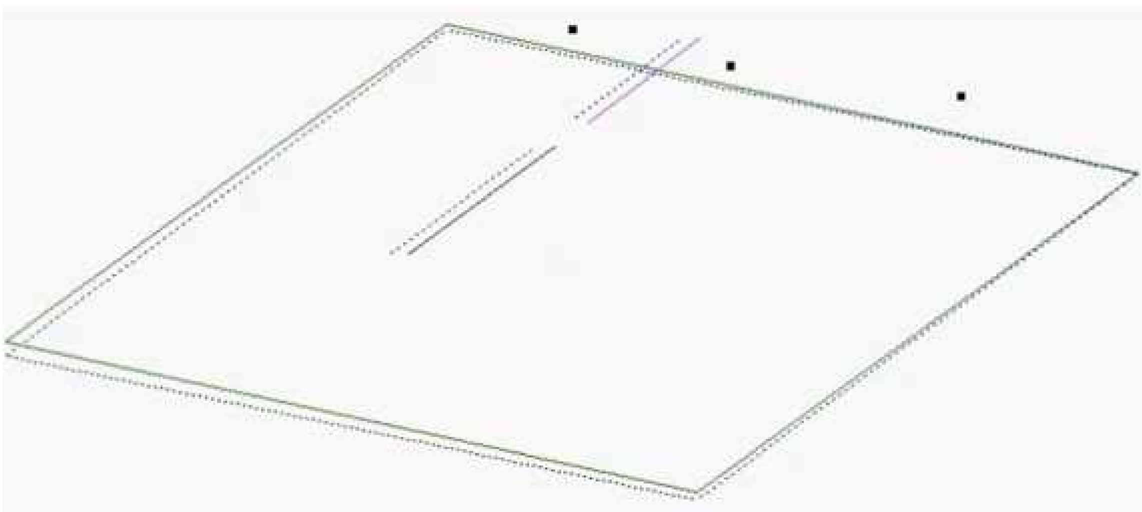

Figure 16: 2x Run Speed ODS

Run Up Waterfall: The run up waterfall data set is similar to the steady state spectrum except that the data is taken during a transient event of the system; therefore, the data is not averaged. Instead, the data is plotted repeatedly stacking up with time. This data tends to be noisier since an average is not calculated. The transient in this case is the pump going from rest to operational speed. The run up of this pump occurred quickly and the data was not significantly different than the steady state spectrum data, aside from the additional noise.

Run Down Waterfall: The run down waterfall data set is taken in the exact same manner as the run up waterfall. The transient in this case is the pump going from operational speed to rest. 'Figure 17' is a representative measurement from the motor, plotted in reverse to aid in viewing. The lines in the front occurred last and the peaks occurred first. A 2x run speed peak is clear and some additional noise is present. The energy dissipates quickly, but some energy remains. This could be cross talk from the already running redundant pump.

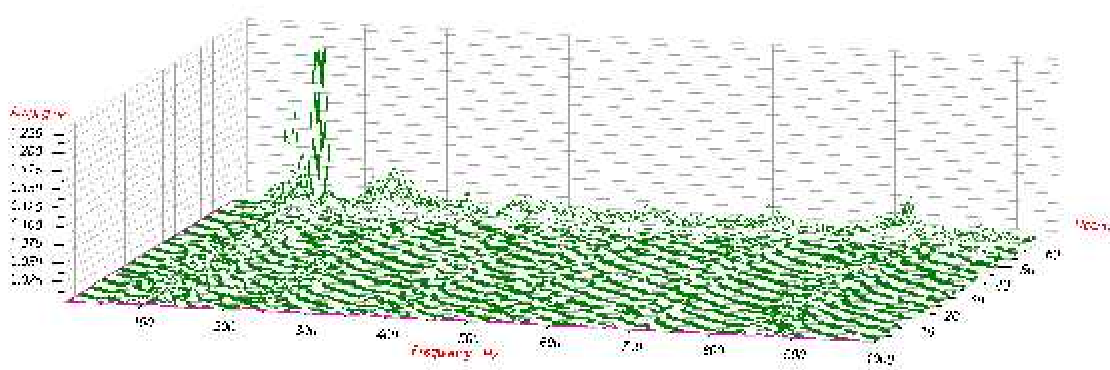

Figure 17: Motor Run Down Waterfall

"Figure 18' is a representative measurement from the pump, also plotted in reverse. A 2x run speed peak is clear. Broadband noise is prevalent and a general peak around 700Hz is present. This peak will be discussed in the modal impact section.

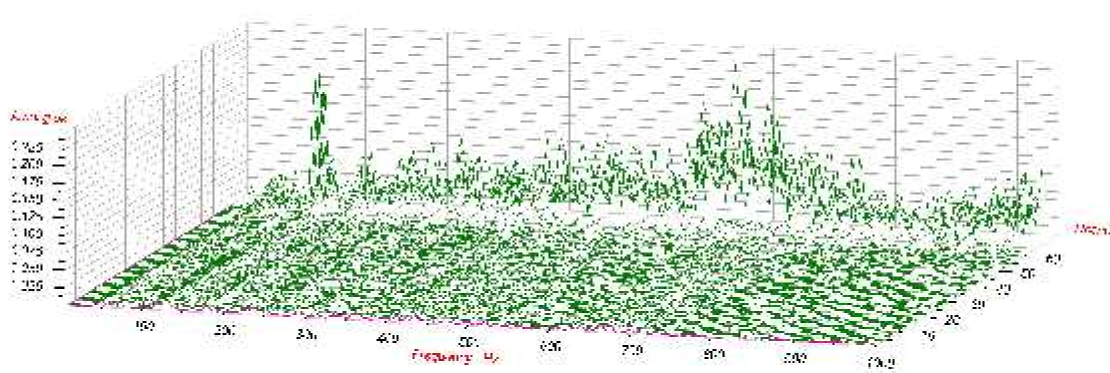

Figure 18: Pump Run Down Waterfall

Stationary Spectrum: The stationary spectrum data set was taken in a similar manner as the steady state spectrum except that the pump has been turned off and is at rest. The neighboring pump, PU-9B, is about ten feet away and has been turned on to continue the supply of cooling water. This data measures cross talk from PU-9B to the accelerometers on PU-9A. ‘Figure 19’ shows that the magnitude of the crosstalk present in the pump is about six percent of the pump during normal operation.

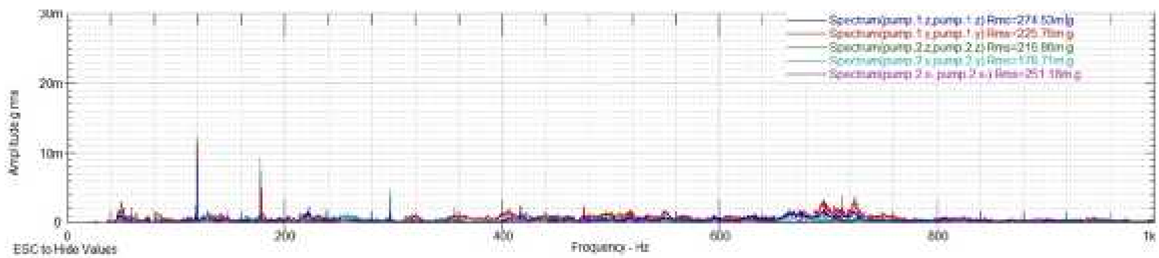

Figure 19: Stationary Pump Spectrum

‘Figure 20’ shows that the magnitude of the crosstalk present in the piping is about twenty percent of piping during normal operation.

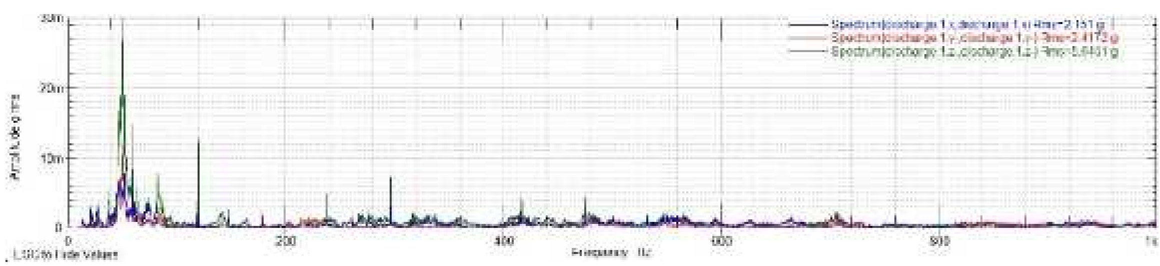

Figure 20: Stationary Discharge Spectrum

These results are expected, given the proximity of the two systems and that they share some common piping.

Modal Impact: The modal impact data set is taken while the pump is at rest. Modal impact analysis was preformed utilizing an additional channel of the data acquisition and a commercial modal impact hammer. Four averages where taken at each impact location and all twenty-six channels were acquired simultaneously. Using the hammer channel as the reference, a Frequency Response Function (FRF) was calculated for each channel. ‘Figure 21’ is a representative data set for the motor. The first modal resonance of the motor occurs at around 700Hz, but the mode does not appear to be excited during normal operation as seen in the steady state spectrum section of this report.

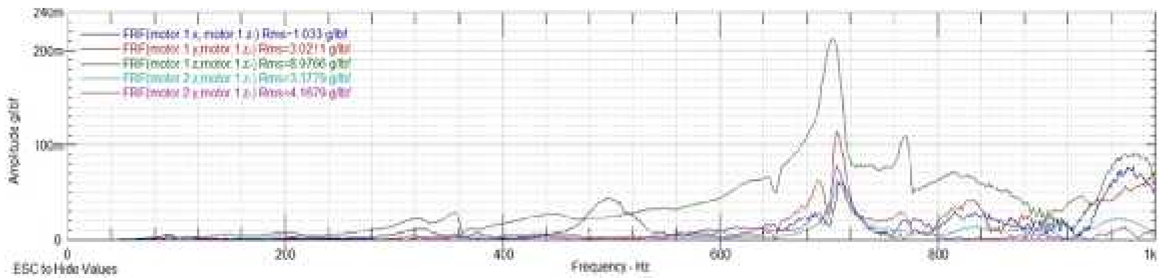

Figure 21: Motor FRF

‘Figure 22’ is a representative data set from the pump. The first modal resonance of the pump occurs at around 740Hz. Some modal interaction with this mode occurs during normal operation as seen in the steady state section of this report, but it is barely above noise level.

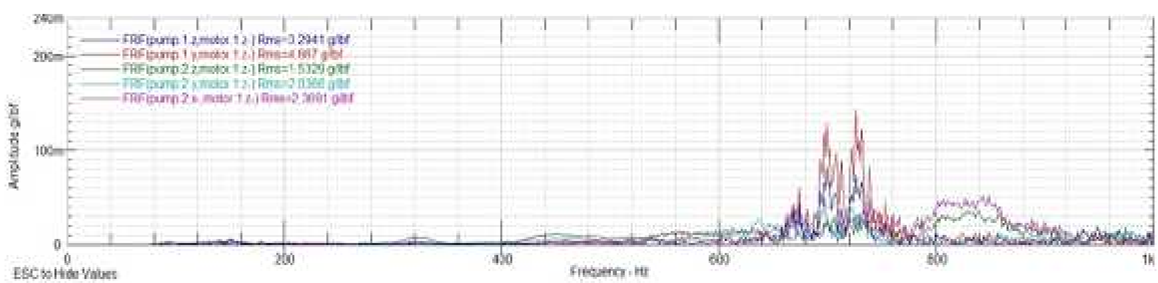

Figure 22: Pump FRF

Analysis Results Summary and Maintenance Suggestions: Overall, the pump is in a good conditional state as per ISO 10816 vibration standard. The 2x run speed vibrations seen in the steady state spectrum data and ODS data are indicative of misalignment in the shaft during operation. The motor's electrical grounding could be checked to rule out electrical fault causing a 120Hz peak and validating that it is in fact misalignment alone. The new bearing frequencies are present but not excessive, therefore, they have not worn out and were not damaged during installation. The high energy broadband noise in the pump spectrum is indicative of hydrodynamic issues such as cavitation. This could possibly be due to inadequate suction head pressure. It is suspected that this is due to piping layout. A piping engineer could verify this and suggest changes. If a piping teardown, redesign, and rebuild takes place, it is suggested that a new concrete and steel base be considered. The only modal interaction observed from the impact test is around 740 Hz at the pump and it is barely above noise level. This interaction could get worse if the cavitation were to get more severe. It is out of range of most other mechanical issues. Some cross talk from PU-9B can be measured on PU-9A when 9B is running, but it is less than twenty percent of the energy of operational 9A.

Conclusion: Due to a recent history of premature bearing failures, one of the two redundant cooling water supply pumps of HFIR at ORNL has undergone maintenance including base looseness and shaft misalignment work. The testing summarized within this report corroborate that the maintenance was effective and that the pump is in a good conditional state. However, some failure modes do persist. The testing setup section lists the equipment used and the locations of the accelerometers on the system. The steady state spectrum section identifies a 2x run speed vibration indicative of shaft misalignment, and broadband noise in the pump is indicative of hydrodynamics issues. The steady state ODS section corroborates the shaft misalignment and identifies base and pipe movement. The run up waterfall section did not add additional information. The run down waterfall section corroborates the 2x run speed vibration in the system and broadband noise in the pump. The stationary spectrum section describes some cross talk from the PU-9B while PU-9B is powered down. The modal impact section, along with the steady state spectrum section, highlight some modal integration during normal operation of the pump at around 740Hz. The analysis results summary and maintenance suggestions section shows that the analysis results do not immediately warrant system maintenance, but indicate areas of future work. The motor's electrical grounding should be checked. The piping layout should be checked by a piping engineer and, if piping work is done, a new concrete and steel base is recommended.

Acknowledgments: This research used resources of the High Flux Isotope Reactor, which is a DOE Office of Science User Facility.