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

DRAFT ①

MEMORANDUM FOR: Vincent S. Noonan, Chief
Equipment Qualification Branch
Division of Engineering

FROM: Jerry E. Jackson
Equipment Qualification Branch
Division of Engineering

SUBJECT: TRIP REPORT - REVIEW OF CE-KSB TESTING OF MODIFIED PALO VERDE REACTOR COOLANT PUMP AT THE NEWINGTON, NH TEST FACILITY

During the period of November 14-16, 1983 J. Jackson (NRR/EQB) and W. McNeill (Region IV) visited the Newington, New Hampshire test and manufacturing facility of Combustion Engineering, Inc. (CE) to review the manufacturing of the CE-KSB reactor coolant pump (RCP) and the current testing of the modified CE-KSB Palo Verde RCP.

W. McNeill's report will address the Region IV findings regarding this trip, however the following facts, events and conclusions regarding the Palo Verde RCP problem and the current testing of the modified pump are worth noting at this time.

General

1. Phase-3 of the RCP test program did not occur during our visit to the site as previously scheduled. This delay was due to an accelerometer which had failed and its replacement had to be shipped from Switzerland.

2. We reviewed the RCP test facility with the engineer in charge, John Leavitt. Charles White, manager of manufacturing at the Newington site showed us through the facility where the pumps are manufactured. We were able to see some of the Palo Verde RCP parts, both those which had failed during hot functional testing and the parts being modified for return to Palo Verde. Vincent Krecicki, Assistant Project Manager for the Arizona Nuclear Power Project also accompanied us to provide information on the Palo Verde RCP problem. We also reviewed the details of the changes being made to the RCP and the reason for these changes with Frazier Colon, manager of engineering at CE-KSB Pump Company, Inc. at Newington.

3. We were told that flow resistance changes only slightly with the core in, therefore problems encountered during hot functional testing without the core are approximately the same as could be experienced during normal operation at Palo Verde [3% difference in flow].

50-528, 529, 530

Contact: J. Jackson, NRR
Ext. 27930

4. CE feels that the problem with broken impeller vane segments is not related to loose and/or broken diffuser and suction pipe retaining cap screws or diffuser vane cavitation. It is felt that these are two distinct and separate problems.

5. The first pump or prototype was tested for 500 hours with approximately 50 or 60 hours of this time at runout (maximum flow). The time at maximum flow during the Palo Verde hot functional testing could have exceeded the test time on the prototype. When the modified RCP's are installed in Palo Verde-1 the hot functional testing will not be repeated, the plans are to only functionally test the pump. This test will be approximately 160 hours to reach an infinite number of fatigue cycles on the diffuser and suction pipe bolts. Also the decision has been made not to subject the modified pumps to the normal 50-hour performance test prior to shipping to Palo Verde. In fact, parts of two of the modified pumps have already been shipped to Palo Verde. Also the decision has been made not to match impellers with diffusers in the future, as was previously done. The reason given being that a mis-matched impeller and diffuser was tested in Phase 1 of the current tests relating to the Palo Verde RCP problem.

6. In the past, three different vendors have supplied impeller castings 1) Schmidt and Clemens, 2) Fisher, and 3) Atlas. The impellers used in Palo Verde previously, those which experienced impeller vane failure, were made by Atlas. The impeller used in the current verification test program was provided by Schmidt and Clemens. The impellers being shipped back to Palo Verde are also Schmidt and Clemens.

7. Dr. E. Makay is the outside consultant being used for design change recommendations. The details for the major change recommended by Dr. Makay (changing diffuser to impeller gap from 2% to 6%) is given in the proceeding from the July 1983 symposium, "Power Plant Feed Pumps - State of the Art", EPRI CS-3158 Contract WS 81-211.

8. During the course of our meeting we have asked for available information, perferably documents, which would allow us to determine if 1) the RCP failure mechanisms had properly been determined and understood and 2) what tests were being performed to determine if the design changes being made would adequately solve the problem.

We were looking for final or preliminary reports on the KSB model tests, Phase 1 and 2 test results and reports on the cause of the impeller failure. Also we expected to see test procedures for one or all of the test phases, as well a complete picture the instrumentation used prior to the Palo Verde failures and in the present four phase test program. None of this information was provided as documents, final or preliminary. However all these issues were discussed in some detail and much valuable information was received.

Pump Modifications

The pump design changes were reviewed on the drawings with F. Colon and V. Krecicki. The major modifications were:

1) Diffuser

- o Radial gap between diffuser and impeller increased from 2% to 6% (material removed from diffuser vane to accomplish this)
- o Number of diffuser bolts increased from 16 to 29, with length increased from 65 mm to 110 mm.
- o Increased thickness of diffuser clamping rings, changed segment size to go from 4 bolt pattern to 2 bolt pattern (increased number of segments from 4 to 14)
- o Increased bolt torque from 130 ft.-lbs. to 260 ft.-lbs. This increased the bolted joint clamping force by a factor of three.

2) Suction Pipe

- o Suction pipe to diffuser joint changed to delete tapered fit and assure positive bolting surface.
- o Four tapered pins were added to the joint
- o Clamping ring added
- o Number of bolts increased from 16 to 24, with length increased from 65 mm to 70 mm
- o Increased torque from 110 ft.-lbs. to 155 ft.-lbs.
- o Deleted sealing rings at bottom of the suction pipe.

3) Impeller

- o Filed trailing edge of impeller vanes to bring head curve back up to design (trailing edge did not fail in hot functional testing)
- o Increased quality control and NDE requirements to assure leading edge of the impeller actually meets design.

Pump Test Facility

The pump test facility was designed and built to performance test centrifugal pumps of vertical, single stage, single suction design in accordance with the requirements of ASME Performance Test Codes. The

facility is capable of testing pumps of this design driven by electric motors with a voltage of 13.2 KV and power ratings as large as 11,931 kilowatts (16,000 horsepower), flow capacities of up to 185,000 gpm, operating temperatures up to 650 F and pressures up to 2500 psia.

The primary loop consists of horizontal runs of 36 inch diameter carbon steel, stainless steel strip clad pipe approximately 70 feet in length jointed by a trifurcated return elbow. The two outside branches incorporate butterfly valves for flow control while the center branch contains a throttling orifice that establishes minimum loop resistance. In order to cover the complete performance range, more than one orifice plate is required. The present test program for the Palo Verde pump uses one orifice plate and therefore can vary flows from 95% to 135% of design and from 140% to 150% of design.

Flow through the loop is measured by means of a calibrated 36 inch by 25 inch universal venturi tube. Piezometers and temperature sensors are located at various positions around the loop to measure pressure and temperature. The fluid in the loop is deaerated, deionized water.

All of the test parameters measured are logged through an integrated computer system. This system provides for logging test data continuously on a magnetic tape for processing at a later time, as well as recording selectable parameters on multipoint or multipen chart recorders for instantaneous analysis. This elminates the necessity of hand written data log sheets. A log will be maintained correlating events to test running time.

Cooling systems provide temperature control of the primary loop water and cooling water for the pump and motor. A portion of the primary loop water is circulated through a water to air heat exchanger. The minimum primary loop water temperature that can be obtained is a function of heat load and environmental conditions.

The closed cooling water system temperature is controlled by an evaporative cooler. Again, the minimum temperature is dependent upon heat load and environmental conditions. A closed system provides for control of a wider temperature range and water quality.

A charging system is provided to control the primary loop pressure and provide water for seal injection. A water heater provides temperature control of the seal injection system.

Instrumentation

The following instrumentation was standard for the 50 hour production testing of a RCP prior to the Palo Verde pump failure.

1. Pump shaft orbit indications
2. Upper bearing housing frame vibration, in three directions, velocity probe integrated displacement meter.

3. Three seal pressures
4. Five seal temperatures
5. Three bearing temperatures
6. One oil temperature
7. Pressure differential across the pump
8. Test loop pressure and temperature downsteam of the venture
9. Loop flow indication

In order to better understand what was occurring inside the pump the test loop pump casing was modified to install additional instrumentation for the four phase testing of the modified Palo Verde RCP. The baseline Palo Verde RCP was to be run from 95% to 135% and 140% to 150% of design flow and then the modified pump hydraulic components for Palo Verde would be installed and the same flow range covered again. It is our understanding that during hot functional testing Palo Verde pumps were operated up to 146% of design flow. However, with the core installed the flow rate would be reduced by approximately 3%. Therefore single pump operation would be at 143% of design flow.

The following additional instrumentation was added to the RCP test facility for this study.

1. One displacement probe will be mounted in the pump casing at the area of the suction pipe piston rings in line with the pump discharge to monitor suction pipe movement.

2. Two pressure transducers will be mounted in the pump casing suction and discharge safe ends at the pressure tap locations to monitor pressure pulsations.

3. Three accelerometers will be mounted in the diffuser at the split located 180° from the discharge. One on the five vane half, and two on the six vane half. These will monitor radial, tangential, and vertical vibration of the diffuser halves. A biaxial and a vertical accelerometer will be mounted on the outside of the pump casing to monitor pump vibration. The difference between the two measurements will be the diffuser movement.

4. Five ring segment bolts will be strain gaged to monitor bolt loadings. The bolt on each side of the diffuser split at discharge and at 180° along with the bolt near the diffuser key on the six vane half. Each bolt will have a thermocouple mounted to it and above it in the water to measure transient thermal conditions.

5. Four thermocouples will be mounted on the top of the pump casing flange outside the pressure boundary to monitor thermal distribution of this surface.

Failure Mechanisms

The supporting information for understanding of the failure mechanisms appears to come from:

1) CE and CE-KSB internal pump experience and knowledge
2) The German KSB model testing of the Palo Verde pump configuration
3) Information provided by Dr. Makay, the consultant
4) Preliminary results of Phase 1 and 2 testing.

None of this information was available to us in the form of documents, preliminary or final. However, we saw a preliminary KSB report on the model testing which was in German, some curves from a paper by Dr. Makay and some of the preliminary bolt stress level results from Phase 1 and 2 testing. The following information was provided to us during the course of our discussion of the problem.

At the higher flow rates there is a mis-match between the impeller blade flow and diffuser vane, since the impeller and diffuser are. sized for the design flow point. As the gap between the diffuser and impeller is increased there is more distance for this flow to adjust. There is indiction that this mis-match is the cause of cavitation on the leading edge of the diffuser vanes. Also as the impeller blades pass a diffuser vane hydraulic forces are imparted to the vane. The larger the gap between the passing impeller blade and the diffuser vane the smaller are the forces which are passed. These forces can be seen at the blade passing frequency and were actually seen at that frequency in the preliminary results from Phase 1 and 2 testing. The primary blade passing frequency can be calculated as follows:

$$f = \frac{2(\text{Pump RPM})\ (\text{Number of Impeller Blades})}{60}$$

$$f = \frac{2(1190)(6)}{60}$$

$$\therefore f = 238 \text{ Hz}$$

Although the final results from Phase 1 and 2 testing where the 2% diffuser gap was used were not available, higher strain and vibration at the high bolt stress area opposite the pump discharge was seen. Also the test engineer saw visual signs of cavitation on the diffuser vane leading edges. The highest delta strain at a frequency of 238 Hz was seen in bolt number nine in the six vane diffuser. This bolt is located 180° from the pump discharge.

We were told that the results of the KSB model test also showed cavitation to occur on the leading edge of the diffuser vanes at 2% gap, but not at the 6% gap. The cavitation was determined visually using fiber optics. The model testing also confirmed the areas of high bolt stress.

The KSB model strain gage testing of the impeller blades showed that the stress in the areas of impeller blades which had failed during the Palo Verde hot functional testing to be well within design limits. Extensive investigations were then made of the impeller castings. These investigations lead KSB to believe that the failures were due to possible thin areas in the impeller blades as well as material imperfections in these areas.

Methods Which Will Be Used To Assure Changes To The Pump Are Adequate

The following results from the four phase test program will be used to assure the changes which have been made to the pump are adequate to solve the problem.

1. Delta strains on the diffuser bolts should be lower in Phase 3 and 4 testing than in Phase 1 and 2.

2. Accelerometer data should indicate less vibration in the diffuser flange during Phase 3 and 4 testing.

3. Pressure pulsation data should show reduced pulsations during Phase 3 and 4 testing.

4. Visual inspection of the RCP should show,

   a) No cavitation marks in the modified pump
   b) Contact surfaces, diffuser to pump casing, suction pipe joint and diffuser clamp segments, should not show signs of wear or movement after Phase 3 and 4 testing.
   c) The bolt torque values should remain high after Phase 3 and 4 testing.

Combustion Engineering also feels that the KSB model testing which verified Dr. Makay's curve for radial hydraulic forces and the fiber optic investigation of the cavitation phenomenon support the fact that the diffuser changes are adequate. They feel that the KSB strain gage tests of the impeller blades and the detailed inspections of the impeller castings support the fact that changes in manufacturing and Q/A are adequate to solve the impeller problem.

The staff will continue to follow the progress of the resolution of the Palo Verde RCP problem. However, we will reserve our conclusions until the results of the testing and final resolution by the applicant are made available.

Jerry Jackson

Jerry E. Jackson
Equipment Qualification Branch
Division of Engineering

cc: See next page

cc: H. Denton
E. Case
R. Vollmer
D. Eisenhut
R. Mattson
T. Speis
J. P. Knight
T. Novak
G. Knighton
V. Noonan
R. Bosnak
U. Potapovs, Region IV
P. Boehnert, ACRS
G. Bagchi
J. Jackson
E. Licitra
W. McNeill, Region IV

2

Palo Verde Nuclear Generating Station
Reactor Coolant Pump
Design Deficiencies
Preliminary Report

Description of Deficiencies

After pre-core hot functional testing of PVNGS Unit #1, Reactor Coolant Pump (RCP) 1A was disassembled to excavate a linear indication in the pump casing circumferential weld. Inspection of the pump internal assemblies revealed 4 broken and 2 loose diffuser to casing retaining cap screws. Three of the four broken cap screw heads came free of their locking devices. Ten of the diffuser to suction pipe cap screws were discovered loose. There was also some slight cavitation damage observed on local areas of the leading edge of 7 of 11 diffuser vanes. The attached tabulation provides a more detailed description of the damage observed in RCP 1A.

Disassembly of the other three Unit #1 RCP's revealed loose and/or broken diffuser and suction pipe cap screws as detailed in the attached tabulation. The pump casings also sustained wear, fretting or peening (RCP1A) damage as shown in the tabulation. The leading edge of one impeller vane on RCP 1B and two vanes on RCP 2A showed missing segments. Varying degrees of minor cavitation were observed on local areas of the leading edges of the diffuser vanes on these three pumps.

In summary, the deficiencies are categorized into three areas:

1. Loose and/or broken diffuser and suction pipe retaining cap screws.
2. Broken impeller vane segments.
3. Diffuser vane cavitation.

Evaluation of Safety Implications

The three deficiencies have been determined to be not significant with regard to safety and therefore not reportable under the criteria of 10CFR50.55(e). If the deficiencies were to have remained uncorrected, they would not have adversely affected the safety of operations of the plant at any time throughout the lifetime of the plant.

C-E has reviewed the potential failure mechanisms and their consequences, including a locked rotor, degraded pump coast down and core flow blockage and has come to the same basic conclusions as stated in our response to DER 82-61. These conclusions are repeated here and amplified upon to address the present situation.

a) During full power operation hydraulic forces alone can maintain the diffuser in place. Only during startup or coast down is there any potential for axial movement of the diffuser. The design is such that the diffuser-suction pipe assembly is captured radially throughout any axial movement. The diffuser can not rotate because it is restrained by two keys which engage the mating pump casing ledge. With these design features the potential for impeller binding is remote during start-up and coastdown.

Although there was some movement of the diffuser/suction pipe assemblies as evidenced by wear on the suction pipe seating surface and the diffuser ledge in the pump casing, there was no evidence of impeller binding. The keys in the diffuser to casing joint prevented radial movement of the diffuser halves. The RCP's with the broken impeller vanes did show some minor scratching on the impeller wear surfaces but not of sufficient magnitude to effect pump coast down.

b) The total assessment of the effects of the cap screw deficiencies and impeller vanes breakage shows that the RCP maintains sufficient flow to satisfy the criteria of the safety analysis.

c) The potential for core flow blockage has been examined and it has been concluded that the three deficiencies would not lead to flow blockage.

The radial gap between the impeller and diffuser is small enough to prevent the escape of particles that are large enough to cause local flow blockage. This conclusion was verified in RCP 1A in that the three broken diffuser cap screw heads which came free from their locking sleeves did not pass through the impeller/diffuser gap.

The broken impeller vane segments were found in the flow skirt of the reactor vessel because they were too large to pass through the flow skirt. The long cracks found in the damaged impellers indicate that any additional segments would be too large to pass through the flow skirt.

Any particles generated from the diffuser vane leading edge cavitation would be microscopic in size and would not lead to core flow blockage. The diffuser vane cavitation observed at PVNGS Unit #1 was minor and no material was found in the RCS which could be identified as diffuser material.

Corrective Action

An intensive program has been initiated at C-E, CE-KSB and KSB (West Germany) to determine the causes of the deficiences, determine necessary modifications and verify the modifications by model and prototype testing. The projects presently underway and planned include the following:

1. Model tests with increased impeller/diffuser gaps to evaluate the reduction in pressure loadings on the diffuser/casing and diffuser/suction pipe joints. The model tests will also determine the effectiveness of increased gaps to eliminate the diffuser vane leading edge cavitation.

2. A complete evaluation of the diffuser and suction pipe cap screw stresses considering imposed loads, bolt preload, dimensional tolerances and stack-up and assembly techniques.

3. A metallurgical investigation of the adequacy of the cap screw and impeller materials. Preliminary results show that both the cap screws and impellers are in compliance with the required material specifications.

4. Model tests to verify known impeller stresses annd look for additional loadings which may result from higher than anticipated runout flows.

5. Development of an impeller selection criteria which considers vane thickness, vane surface finish, weld repair history and non-destructive testing.

6. Prototype testing in the CE-KSB test loop to collect base line data on the hydraulic components as originally designed and as modified. This testing will also include verification of the adequacy of diffuser retention modifications.

C-E will report on the results of the program in a final corrective action report.

3