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Technical Report on Lessons Learnt with AP1000 Reactor Coolant Pumps

Participation

Regulators involved in the MDEP working group discussions:	CNSC (Canada), NNSA (China), AERB (India), ONR (UK), NRC (U.S.)
Regulators that support the present technical report:	CNSC (Canada), NNSA (China), AERB (India), ONR (UK), NRC (U.S.)
Regulators with no objection:	none
Regulators that disagree:	none

Introduction

This technical report describes the design, manufacturing and testing of the reactor coolant pump (RCP) used in the AP1000 Nuclear Power Plants (NPPs). The testing includes prototype and commissioning tests. This report focuses on the regulatory practices, cooperative regulatory experiences, and lessons learnt related to the RCPs.

Description of AP1000 RCPs

The AP1000 NPP reactor coolant system (RCS) consists of two heat transfer circuits, each with two RCPs installed. The pump casings of the two RCPs are directly welded onto the channel head of each steam generator at the suction nozzle. The RCPs casings are an integral part of the RCS pressure boundary and are nuclear safety-related. The pumps also have a nuclear safety-related requirement to meet a specified flow profile during coastdown following de-energization. AP1000 RCPs are vertical, single-stage, high-inertia, seal-less pumps controlled by variable frequency drives. The RCP seal-less feature eliminates the small Loss of Coolant Accident (LOCA) due to seal failure. While all AP1000 plants use seal-less RCPs, the design of the pumps is not the same. The pump designs are similar for the plants in the People's Republic of China and in the United States (US), but the design is different in the United Kingdom (UK). The AP1000 designs in the US and China use a canned-motor pump; while the design in the UK uses hermetically sealed wet winding RCPs.

The main differences in design between the RCPs used in China and the US, as compared to the UK design, are the following:

1. Primary coolant circulates through the stator windings and the gap between the rotor and stator in the UK design. For the RCPs in China and US plants, the electrical parts of the stator and rotor are segregated from the primary coolant by the stator can and rotor can, respectively.
2. The wet winding motor concept has a higher efficiency when compared to the canned motor design given its high eddy current losses.
3. RCPs in the UK have one flywheel located between the impeller and the motor. The flywheel consists of a single-piece forged stainless steel cylinder with several smaller heavy metal cylinders inside. In the China and US RCPs, there are two flywheels and each flywheel consists of a heavy alloy segment, stainless steel hub and a retainer cylinder. The upper flywheel is located between the motor and impeller, while the lower assembly is located below the canned motor with the thrust bearing.
4. In the UK design, the pump casing is a single-piece forging, fabricated of ferritic material (SA508-3) and has corrosion-resistant cladding on surfaces exposed to the reactor coolant. The RCPs casings in China and the US are cast using CF8A material.

The remainder of this report focuses on the RCPs being used in China and US projects; since construction of the AP1000 design is not currently planned in the UK.

The AP1000 will be the first design using these pumps, since canned-motor pumps of the size required for the AP1000 design have not been built before. The vendor conducted a First of a Kind (FOAK) test program for the canned-motor RCPs as part of design verification. Manufacturing began in February 2008, and the first series of tests started in September 2009. The series included diagnostic, engineering, endurance, and production tests. During the design and manufacturing of the RCPs, multiple design changes and test verifications were made to parts such as the lower flange, thrust bearing, impeller and thrust runner. The first batch of AP1000 RCPs was shipped in November of 2015.

AP1000 RCP Lead Unit Prototype Test

In accordance with the requirements of the RCP test and design specifications, 20 engineering and endurance tests were to be completed on the AP1000 canned-motor RCP lead unit. The vendor initially conducted engineering and endurance tests on two separate RCPs instead of the same RCP. After the subsequent production test and disassembly inspection, a series of issues like impeller blade damage, thrust runner pitting, thrust runner heat checking and thrust bearing damage were observed. To address these issues, modifications were made related to thrust runner materials, the manufacturing process, bearing design, operating conditions, and control logic. In order to further verify the adequacy of the modified design, additional engineering and endurance tests were performed.

In 2014, National Nuclear Safety Administration (NNSA) received the AP1000 RCP Engineering and Endurance Retest Program and its supplemental documents from the applicant. Considering that a series of quality issues occurred during the manufacturing and testing of the RCPs, NNSA set up a dedicated team to review the AP1000 RCP non-conformance reports and the AP1000 RCP Engineering and Endurance Retest Program. In addition, the team members had in-depth technical discussions with the applicant, Westinghouse and their supplier focusing on the following issues: (1) completeness, adequacy and effectiveness of the tests; (2) the finite element analysis and (3) the number of Loss of Coolant Water (LOCW) tests.

In February 2015, NNSA imposed nuclear safety requirements that specify that the vendor was not to deliver the RCPs until successful completion of prototype testing occurred. These tests were divided into three categories: RCP hydraulic performance, motor performance, and operation transient performance tests, with no less than the following 15 specific tests:

1. Cold Performance Characteristics Test
2. Hot Performance Characteristics Test
3. Electrical Balance Test
4. Hot Insulation Resistance Test
5. Load Slip Test
6. Service Cycle Test
7. Pressure Pulsation Measurement Test
8. Reduced Voltage Hang Up Test
9. Loss of Power Test
10. Loss of External Cooling Water Test
11. Operational Test
12. Reverse Rotation Operability Test
13. Forward Restart of Reverse Rotating RCP Test
14. Net Positive Suction Head Test
15. Coastdown Test

Inspection activities

U.S. Nuclear Regulatory Commission (NRC) Experience

The NRC conducts vendor inspections at vendor facilities principally to examine whether the vendor has been complying with Appendix B, “Quality Assurance Criteria for Nuclear Power Plants and Fuel Processing Plants,” to Title 10, Part 50, “Domestic Licensing of Production and Utilization Facilities,” of the Code of Federal Regulations (10 CFR Part 50), as required by procurement contracts with licensees. Notices of Non-conformances or Notices of Violations are issued to vendors for failures to meet quality commitments or the requirements of 10 CFR Part 21, "Reporting of Defects and Noncompliance," respectively. The Inspection Procedures (IPs) that were used in the following inspections included:

- IP 36100, “Inspection of 10 CFR Part 21 and 50.55(e) Programs for Reporting Defects and Non-conformance,”
- IP 43002, “Routine Inspections of Nuclear Vendors,” IP 43004, “Inspection of Commercial-Grade Dedication Programs,” and
- IP 65001.A, “Inspection of the As-Built Attributes for Structures, Systems, and Components (SSCs) Associated with ITAAC.”

The NRC conducted several inspections of the RCP vendor between 2009 and 2016.

2009 NRC Vendor Inspection

The initial inspection report can be viewed at:
https://www.nrc.gov/docs/ML0932/ML093220003.pdf. The results of this inspection are summarized below.

With the exception of one violation and two non-conformances described below, the NRC inspection team concluded that the manufacturer’s QA policies and procedures complied with the applicable requirements of 10 CFR Part 21 and Appendix B to 10 CFR Part 50. The NRC inspection team further concluded that the vendor personnel were implementing these policies and procedures effectively.

The NRC inspection team identified a violation involving multiple examples of manufacturer’s failure to meet the requirements of 10 CFR Part 21. The NRC cited the violation because the vendor did not provide adequate procedural guidance to evaluate deviations and failures to comply associated with substantial safety hazards, and the manufacturer failed to make an interim report regarding a Part 21 evaluation that was ongoing for more than 60 days.

The NRC inspection team identified two non-conformances associated with the vendor’s failure to meet the requirements of Criterion III, “Design Control,” of Appendix B to 10 CFR Part 50. The first non-conformance identifies the vendor’s failure to reference the design bases and other appropriate documents which specify operating requirements in the RCP external heat exchanger design specification.

The second non-conformance identifies the vendor’s failure to provide documented evidence that the technical review activities required by their design review process had been performed. With the exception of these issues, the NRC inspection team concluded that the vendor's design control process conforms to regulatory requirements and has been implemented in accordance with the applicable vendor policies and procedures.

2014 NRC Vendor Inspection

The initial inspection report can be viewed at: https://www.nrc.gov/docs/ML1424/ML14240A517.pdf. This limited-scope inspection, which included an observer from NNSA, specifically evaluated the vendor's implementation of quality activities associated with designing and manufacturing the RCPs for the AP1000 reactor design.

These RCPs were being fabricated for the Vogtle Electric Generating Plant (VEGP), Units 3 and 4 and Virgil C. Summer Nuclear Station, Units 2 and 3. Because of an ongoing re-design of the RCP lower thrust bearing and lower flywheel, this was a limited scope inspection that concentrated on organization, the QA program, nonconforming materials, parts and components, corrective actions, and limited portions of design control. The results of the inspection are summarized below:

The NRC inspection team issued a non-conformance in association with the vendor's failure to implement the regulatory requirements of Criterion XVI, "Corrective Action," of Appendix B to 10 CFR Part 50. The non-conformance cites the vendor for failing to ensure that significant conditions adverse to quality were promptly identified and corrected, failing to ensure that significant conditions adverse to quality were corrected to preclude repetition, and failing to perform effectiveness reviews (EFR) for significant conditions adverse to quality, as required by the vendor's corrective action program.

The NRC inspection team determined that the vendor was implementing its programs for nonconforming materials, parts or components, design control and the quality assurance program in accordance with the applicable regulatory requirements of Appendix B to 10 CFR Part 50. Based on the limited sample of documents reviewed and activities observed, the NRC inspection team also determined that the vendor was implementing its policies and procedures associated with these programs. No findings of significance were identified.

2016 NRC Vendor Inspection

The initial inspection report can be viewed at: https://www.nrc.gov/docs/ML1635/ML16350A067. This technically-focused inspection specifically evaluated the vendor's implementation of quality activities associated with the design. The following specific activities related to an RCP to be used internationally were observed by the NRC inspection team:

- Slip testing of an international RCP
- Coastdown testing of an international RCP
- Overspeed testing of the lower flywheel for a domestic RCP
- Penetrant Inspection of Weld No. 44 for the lower seal ring canopy of an international RCP
- Welding of the thermal barrier/diffuser locking device for an international RCP
- Stud heating and torqueing for an international RCP
- Flip and interference fit of flywheel onto rotor for an international RCP
- Lower thrust bearing assembly for an international RCP

- Graphite shoe inspection for an international RCP
- Stator assembly for an international RCP
- Rotor balancing for a domestic RCP
- Receipt inspection of a graphite thrust shoe insert for a domestic RCP

With the exception of two non-conformances described below, the NRC inspection team concluded that the vendor's QA policies and procedures comply with the applicable requirements of Appendix B to 10 CFR Part 50 and 10 CFR Part 21, and that the vendor's personnel are implementing these policies and procedures effectively. The results of this inspection are summarized below.

Design Control

The NRC inspection team issued a non-conformance regarding the vendor's failure to implement the regulatory requirements of Criterion III, "Design Control," of Appendix B to 10 CFR Part 50. The non-conformance cites the vendor for failing to transfer all pertinent design requirements into applicable instructions and failing to use the material specified in the design specification. Specifically, Alloy 600 weld filler material was used for weld numbers 37, 38, 39, and 61 of all flywheel enclosures. By not correctly transferring the material requirements to the vendor drawings and weld procedures, the flywheel enclosure welds were not made of Alloy 625 material, as required by the AP1000 Design Specification APP-MP01-M2-001.

Control of Purchased Material, Equipment, and Services

The NRC inspection team issued a non-conformance in association with the vendor's failure to implement the regulatory requirements of Criterion III and Criterion VII, "Control of Purchased Material, Equipment, and Services," of Appendix B to 10 CFR Part 50. The non-conformance cites the vendor for failing to verify through the conduct of a commercial-grade survey or another acceptance method that certain critical characteristics identified in the technical evaluation of the impeller casting, impeller weld repair, and calibration services were adequately controlled. The vendor's commercial-grade survey of a supplier did not verify that the supplier had imposed and verified the necessary controls on their commercial sub-suppliers for performing hot isostatic pressing activities and control and testing of weld filler material. In addition, the vendor's commercial-grade survey of a second supplier did not verify that they had imposed and verified the necessary controls on their commercial sub-suppliers for the calibration of the second supplier's equipment. For both of these suppliers, the vendor did not perform any additional verification or acceptance activities to ensure that the identified critical characteristics were adequately controlled and the components would perform their intended safety function.

Other Inspection Areas

The NRC inspection team determined that the vendor was implementing its programs for 10 CFR Part 21, Test Control, Control of Special Processes, Identification and Control of Material, Parts, and Components, Nonconforming Material, Parts, or Components, Corrective Actions, Control of Measuring and Test Equipment, and Inspection in accordance with the applicable regulatory requirements of Appendix B to 10 CFR Part 50. Based on the limited sample of documents reviewed and activities observed, the NRC inspection team also determined that the vendor is implementing its policies and procedures associated with these programs.

People's Republic of China, National Nuclear Safety Administration (NNSA) Vendor Inspection Experience

The NNSA set up an office in the US for vendor inspections. Two comprehensive inspections were conducted in 2012 and 2014. A special inspection of the RCP engineering and endurance retest was conducted jointly with the NRC in 2015.

2012 NNSA Vendor Inspection

The initial inspection report can be viewed at: http://nro.mee.gov.cn/haqsbjd/jxsbjd/201607/t20160708_359141.shtml. The results of this inspection are summarized below.

The vendor has registered design and manufacturing of civil nuclear safety-related facilities according to China's nuclear safety regulations and its design and manufacturing for Sanmen and Haiyang RCPs are within the scope of registered activities. The vendor has effectively rectified the concerns raised by NNSA regarding daily supervision according to nuclear safety requirements.

During the inspection of procurement technical documents and CMTR of flywheel retainer ring and base ring, it was found that the requirements and results of toughness test for the base ring were missing, which violates ASME NB-2310 and other technical requirements.

With the attempt to use the Lead Unit as a Product Pump, the vendor conducted analysis and assessments in terms of the aging of motor insulations, fatigue damage of mechanical components and abrasion of bearings (thrust bearing, radial bearing and bearing sleeve) etc. It was found that tiny abrasions occurred after the pump ran for 500 hours and after it started up and shut down 553 times. The test report stated that such abrasions were within allowable design range. However, NNSA did not consider this a forceful argument or an effective demonstration that the RCP can satisfy the 60-year service life requirement.

2014 NNSA Vendor Inspection

The initial inspection report can be viewed at: http://nro.mee.gov.cn/haqsbjd/jxsbjd/201607/t20160708_359261.shtml. The results of this inspection are summarized below.

The NNSA inspection team found that in the HAF604 Quality Assurance Program Manual, there was no description about the external and internal interfaces, neither the definitions of responsibilities nor a description of how they work. This is not consistent with ASME NQA-I-1994 requirements, which states in section 3.2.1 "The external interface between organizations and the internal interfaces between organizational units, and changes thereto, shall be documented. Interface responsibility shall be defined and documented".

The inspection team found that the vendor used a Material Review Report (MRR) to control nonconforming items under manufacturing. This did not meet the requirements for procurement documents, which requires using a Deviation Notice (DN) to report deviations.

The team found that the vendor did not record current, voltage, and speed; which are critical to heat input, in the welding process record for Sanmen Unit 2 thermal barrier. In addition, there were no specific drawings and control requirements in the manufacturing process for UT calibration blocks of Sanmen Unit 2, NO.2 weld.

NNSA inspection team found welding current, voltage, and speed values recorded for the PQR 30038; however, the PQR 30040 recordings were not actual values but ranges.

2015 Joint Inspection on the RCP Engineering and Endurance retest by NNSA and NRC

Test plan met the requirements of ASME NQA-1, especially in obtaining appropriate approvals, establishing test parameters, method of data recording, instructions for actions to take for deviations, precautions during testing, and description of how test results would be evaluated. The inspector checked the vendor's management procedure (ISP E27) in terms of engineering document signature. All the documents reviewed were evaluated to assure proper approval, as required. The Test plan defined all the engineering test requirements and identified test requirements for the lead unit and the product RCPs in technical specification.

Inspectors reviewed "Product Acceptance Instruments Checklist", and inspected calibration status of some instruments. Three instruments indicated overdue calibration, however, those instruments were not tagged or segregated as required, which were not in compliance with the requirements of NQA-1 or the Quality Management Manual.

The observations from the RCP design and manufacturing inspection indicated that the previous quality incidents with the RCPs were caused by inadequacies in the design process, insufficient personnel qualification assessments, process control inadequacies, insufficient subcontractor oversight, inadequate control during manufacturing, and a poor operator's awareness to quality.

Commissioning inspection

The NNSA organized an inspection team with internal and external experts for a special inspection on the commissioning test "Reactor Coolant System RCP Cold and Hot Pre-core Hot Functional Test Preoperational Test". The scope and main contents of RCP commissioning inspection included whether:

- Test preparations for RCP commissioning tests met the prerequisites;
- RCP commissioning tests met QA related requirements;
- Reasonable risk control measures were considered during RCP commissioning tests;
- Data from the the RCP commissioning tests was documented;
- RCP commissioning test results met the related acceptance criteria.

The NNSA inspection team checked the test prerequisite verification, witnessed the RCP performance test at the 291°C (557°F) plateau and the coastdown test, and reviewed the test reports.

The NNSA inspection team focused on the following aspects:

Revise acceptance criterion of RCP coastdown test

The coastdown test results of Haiyang Unit 1 showed failure to meet the acceptance criterion initially given by the designer. The designer re-calculated the acceptance criterion by considering the updated RCP characteristics curve and the drag coefficient, and conducted the safety analysis to verify the impact on the safety margin. The analysis results indicated that the revised acceptance criterion did not impact the conclusion of the accident analysis and the required safety margin is maintained. Therefore, the Haiyang Unit 1 RCP coastdown test results met the revised acceptance criterion. The NNSA inspection team considered it acceptable.

RCPs Vibration Alarm

During the RCPs tests of Sanmen Unit 1, when the speed increased from 50% to 88% for the first time, the RCPs vibration high flash alarm appeared. The vendor analyzed the vibration data and concluded that the alarm signal resulted from low frequency vibration (below 10HZ) and it was not caused by mechanical failure. The vendor evaluated the effect of vibration on the steam generator and the RCPs and concluded that the vibration level observed were low and did not cause a safety concern. The licensee installed digital filter with a 15HZ cut-off on the vibration monitors to prevent activating alarms due to vibration at low frequency.

Commissioning inspection conclusion

The NNSA inspection team concluded that all concerns had been dealt with properly and that the test results met the requirements.

Lessons Learnt with AP1000 Reactor Coolant Pumps

1) Early, meaningful, and in-depth engagement with the vendor should be conducted; particularly with FOAK component.
2) International cooperation including joint inspections and timely information sharing can provide regulators with better tools and improved efficiency to more effectively perform their safety mission.
3) For designs with uncommon features (e.g., AP1000 flywheel and thrust runners), it is prudent to expect and plan for early and extensive testing and inspections to validate the design.
4) Setting up highly experienced teams with experts from the nuclear industry and research institutions resulted in a more effective and efficient inspection and a greater understanding of the equipment, its capabilities, its safety requirements and its compliance with the regulations.
5) Look for the vendor to display design review capabilities in order to reduce nuclear safety risks and equipment reliability impacts caused by insufficient design. The vendor should identify the design problems during the design stage and take timely measures to address them.
6) Ensure the vendor has a strong quality management and oversight of subcontractors including the procurement process.
7) Ensure licensees prepare a process to address test exceptions before RCP commissioning tests to promptly take corrective action to address test deficiencies encountered during commissioning tests.
8) Verify that the acceptance criteria of the tests are in compliance with the safety design requirements and are clearly identified. Any changes to the acceptance criteria should be adequately justified.
9) The vendor should consider provisions identified in the Common Position on the Design and use of Explosive - Actuated (SQUIB) Valves in Nuclear Power Plants (AP1000-01), http://www.oecd-nea.org/mdep/common-positions/PUBLIC%20USE%20DCP-AP1000-01-%20Squib%20valves.pdf, that may be applicable to a FOAK component being evaluated.

List of Reference Documents

1. HAF102 Safety Rules for Nuclear Power Plant Design
2. HAF103 Safety Rules for Nuclear Power Plant Operation
3. American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code
4. Final Safety Analysis Report of Unit 1 and 2 of Sanmen Nuclear Power Plant
5. Final Safety Analysis Report of Unit 1 and 2 of Haiyang Nuclear Power Plant
6. Sanmen Nuclear Power Plant Unit 1 "Cold Hydro and Hot Functional Tests of RCP Prior to Fuel Loading of Reactor Coolant System" Commissioning Inspection Report
7. Haiyang Nuclear Power Plant Unit 1 "Cold Hydro and Hot Functional Tests of RCP Prior to Fuel Loading of Reactor Coolant System" Commissioning Inspection Report
8. U.S. Code of Federal Regulations, Title 10, Part 50, “Domestic Licensing of Production and Utilization Facilities,” Appendix B, “Quality Assurance Criteria for Nuclear Power Plants and Fuel Processing Plants,”
9. U.S. Code of Federal Regulations, Title 10, Part 21, "Reporting of Defects and Noncompliance,"
10. U.S. Nuclear Regulatory Commission, Inspection Procedure 36100, “Inspection of 10 CFR Part 21 and 50.55(e) Programs for Reporting Defects and Non-conformance,”
11. U.S. Nuclear Regulatory Commission, Inspection Procedure 43002, “Routine Inspections of Nuclear Vendors,”
12. U.S. Nuclear Regulatory Commission, Inspection Procedure 43004, “Inspection of Commercial-Grade Dedication Programs,”
13. U.S. Nuclear Regulatory Commission, Inspection Procedure 65001.A, “Inspection of the As-Built Attributes for Structures, Systems, and Components (SSCs) Associated with ITAAC,”