Multi-National Design Evaluation Programme (MDEP)
AP1000 Working Group

Design-Specific Technical Report
TR-AP1000WG-06

Technical Report on
Hot Functional and Startup Testing
Lessons Learnt

Participation

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

1. Introduction

This technical report discusses lessons learnt from the AP1000 Hot Functional Testing (HFT) and Startup testing performed at Sanmen Unit 1 and Haiyang Unit 1 in the People's Republic of China. These lead units completed HFT in 2016, Hot Supplemental Testing (HST) in 2017 and Startup Testing in 2018. As a result of the HFT conducted in China, the designer, the China licensees, and their contractors identified and resolved several design, material, and performance issues. In addition, the testing allowed the designer to identify design changes that were later applied to other AP1000 units and identified opportunities that may provide additional flexibility for plant operations and possibly be incorporated into future HFT and startup testing programs. Regulator involvement in the testing program also resulted in recommendations for regulatory agencies. The China nuclear safety regulator, the National Nuclear Safety Administration (NNSA), and the Eastern Regional Office (ECRO) organized an inspection and review team which was stationed onsite. The team included specialists in system operations, auxiliary systems, instrumentation and control, and safety systems and played an important role in overseeing the commissioning of the initial AP1000 units at Sanmen and Haiyang. At Sanmen Unit 1, NNSA and ECRO inspected 79 commissioning tests, including 32 startup tests, and at Haiyang Unit 1, NNSA and ECRO inspected 76 tests, including 28 startup tests.

2. Description of AP1000 HFT and Startup Testing

2.1 HFT Overview

The main purpose of HFT of the Nuclear Steam Supply System is to verify functions of relevant equipment and systems (including safety-related functions, defense-in-depth and other functions) at corresponding system temperature and pressure to demonstrate they meet design requirements and operate appropriately according to technical specifications. In addition, the operators can obtain actual knowledge and skills of operations with relevant operating procedures and periodic test procedures.

The AP1000 HFT contains seven temperature plateaus. According to the AP1000 design, the first three units need an extra heatup and cooldown cycle to conduct the First Plant Only Tests (FPOTs) and the First Three Plant Only Tests (F3POTs). Normally, subsequent AP1000 reactors should require only one heatup and cooldown cycle to perform all HFT procedures.

2.2 HFT Process

The Sanmen Unit 1 and Haiyang Unit 1 HFT consisted of two heat-up and cooldown cycles：

- Cycle 1: Sanmen Unit 1 and Haiyang Unit 1 went through a process to better prepare them for operation and conducted HFTs. Additionally, for Sanmen Unit 1, several FPOTs were conducted including the Comprehensive Vibration Assessment Program (CVAP) for reactor internals and the Pressurizer Surge Line Thermal Stratification Evaluation.
- Cycle 2: Other FPOTs and F3POTs conducted during HFT included the Passive Residual Heat Removal Heat Exchanger (PRHR HX) Heat Transfer Capability Test, the Core Make-up Tank (CMT) Recirculation Test, the CMT Drain Down test, and the Automatic Depressurization System (ADS) Blowdown Test. Additional testing and the remaining HFTs were conducted.

2.3 FPOT and F3POT during AP1000 HFT

- **Reactor Vessel Internals (RVI) CVAP Test, FPOT**

The purpose of the RVI CVAP Test is to verify the structural integrity of the RVI with respect to flow-induced vibration, and to confirming the long-term, steady-state vibration response of the reactor internals for operating conditions.

- **Pressurizer Surge Line Thermal Stratification Evaluation, FPOT**

The purpose of the Pressurizer Surge Line Thermal Stratification Evaluation is to monitor and record the temperature distribution and thermal displacement of the pressurizer surge line.

- **In Containment Refueling Water Storage Tank (IRWST) Heat-up Test, FPOT**

The purpose of the IRWST Heat-up Test is to establish the temperature distributions in the IRWST during the PRHR HX test to confirm the IRWST heat removal capability.

- **CMT Re-circulation and Drain Down Test, F3POT**

The purpose of the CMT Re-circulation and Drain-Down Test is to verify that the CMT provides Reactor Coolant System (RCS) emergency injection and borating function by measuring CMT recirculation. The purpose of the CMT blowdown test is to verify the transition of the CMT from recirculation mode to drain down mode or steam compensation mode.

- **ADS Blowdown Test, F3POT**

The purpose of the ADS Blowdown Test is to verify the correct operation of ADS Stages 1, 2, and 3 valves by discharging the RCS, and to verify that the ADS pressure impact to the IRWST wall meets design requirements.

2.4 Startup Testing Overview

The startup test program begins with initial fuel loading. There are four categories of startup tests:

- Tests related to initial fuel loading
- Tests performed after initial fuel loading but prior to initial criticality
- Tests related to initial criticality and those performed at low power (less than 5 percent)
- Tests performed at power levels greater than 5 percent

During performance of the startup test program, the plant operating staff has the opportunity to obtain practical experience in the use of normal and abnormal operating procedures while the plant progresses through heatup, criticality, and power operations. The general objectives of the startup test program are:

- Install the nuclear fuel in the reactor vessel in a controlled and safe manner.
- Verify that the reactor core and components, equipment, and systems required for control and shutdown have been assembled according to design and meet specified performance requirements.
- Achieve initial criticality and operation at power in a controlled and safe manner.
- Verify that the operating characteristics of the reactor core and associated control and protection equipment are consistent with design requirements and accident analysis assumptions.
- Obtain the required data and calibrate equipment used to control and protect the plant.
- Verify that the plant is operating within the limits imposed by the Technical Specifications.

2.5 FPOT during AP1000 Startup Testing

- **PRHR HX Natural Circulation, FPOT**

The purpose of the PRHR HX Natural Circulation Test is to measure the natural circulation flow rate and the PRHR HX inlet and outlet temperatures to verify that the component meets the design acceptance criteria. This test is only required to be performed once because its purpose is to obtain data to benchmark the operator training simulator.

- **Steam Generator Natural Circulation, FPOT**

The purpose of the Steam Generator Natural Circulation Test is to measure the reactor vessel inlet and outlet temperatures to verify that the component meets the design acceptance criteria. This test is only required to be performed once because its purpose is to obtain data to benchmark the operator training simulator.

- **Rod Cluster Control Assembly (RCCA) Out-of-Bank Measurements, FPOT**

The purpose of the RCCA Out of Bank Measurements is to demonstrate the sensitivity of the incore and excore instrumentation system to RCCA misalignments, the design conservatism for predicted power distributions with a fully misaligned RCCA, and to monitor the power distribution following recovery of a misaligned RCCA. The test is required to be performed only for the first plant because its purpose is to validate calculation tools and instrument responses.

- **Load Follow Demonstration, FPOT**

The purpose of the Load Follow Demonstration is to demonstrate ability of the AP1000 plant to follow a design basis daily load follow cycle and to respond to grid frequency changes while in the load follow cycle. The AP1000 performs load follow with grey rods, as opposed to current Westinghouse pressurized water reactors which manipulate RCS boron concentration to perform load follow operations. The test was included for the first plant to demonstrate the ability of the AP1000 plant to load follow.

3. Issues and Opportunities Identified During HFT in China

3.1 CVAP Test Issues (NNSA)

During the Sanmen Unit 1 HFT, numerous minor issues were identified with the equipment installed for the test. However, the final evaluation of the test results demonstrated acceptability with respect to the design criteria for CVAP. This FPOT was determined not to be needed for Vogtle Units 3 and 4 in License Amendment 151/150 (ADAMS Accession No. ML18351A342) based in part on the results reviewed from Sanmen Unit 1.

3.2 Safety-related Pipe Vibration (NNSA and designer)

During HFT of Sanmen Unit 1 and Haiyang Unit 1, when the system was brought up in power, vibration was observed in one system's piping. That part of the system was redesigned to try to limit the vibration. As a result of the changes, the vibration was found to be significantly reduced to where acceptance criteria were met during follow-on testing.

3.3 CA31 Module Neutron Shield Blocks Silicon Boron Agent (NNSA and designer)

During Sanmen Unit 1 and Haiyang Unit 1 HFT, shielding material in containment did not perform as expected. The designer performed analysis and modified the shielding design to better shield parts of the containment in the CA31 module. This issue was addressed at Vogtle Units 3 and 4 through implementation of the revised Technical Report WCAP-17938, Revision 3, "AP1000 In-Containment Cables and Non-Metallic Insulation Debris Integrated Assessment" (ADAMS Accession No. ML18121A237).

3.4 MN20 Module– Unexpected High Temperature (designer)

Multiple challenges were identified during both HFTs at Sanmen Unit 1 and Haiyang Unit 1 related to the performance of the insulation design in the MN20 module. The designer modified the Containment Recirculation Cooling System flow, insulation, and module structure to address the concerns.

3.5 ADS Blowdown Test (designer)

During HFT of Sanmen Unit 1, the designer identified that valves in the system that did not function as expected. They modified the valves and improved instrumentation during testing to better monitor the valves.

3.6 Thermal Effects, Dynamic Events, and Vibration (TEDEV) Testing

TEDEV Testing including monitoring and data analysis involved significant critical path work during HFT. Minimal findings were identified at Sanmen Unit 1 and Haiyang Unit 1 for the amount of effort involved. Programmatically ensuring piping systems and supports are installed properly can eliminate engineering analysis during HFT and ensure that site walk-downs are focused on validating supports and specific clearances and gaps. Moving forward, a study of the TEDEV program and required instrumentation is recommended to optimize and enhance the TEDEV test program. Based on the results from Sanmen Unit 1 and Haiyang Unit 1, there appears to be potential to simplify the TEDEV testing.

3.7 CVAP, FPOT and F3POT

The FPOTs and F3POTs, which include the RVI CVAP, are tests to further establish and verify performance parameters of the AP1000 design. Based on the standardization of the AP1000 design, it is expected that these tests would only be needed for the first plant or the first three plants. The potential exists to eliminate the FPOTs and F3POTs from future plant commissioning programs based on the successful testing at Sanmen and Haiyang. The elimination of these tests would result in significant cost, schedule, and risk reduction benefits. However, the elimination of these tests would require a dedicated licensing and engineering effort to justify that the results from Sanmen and Haiyang are representative of future AP1000 plants. An additional consideration is that crediting the testing conducted in China would relieve other AP1000 RCSs from being required to undergo the severe design transients associated with conducting the tests, potentially retaining additional margin into component designs. Vogtle Units 3 and 4 completed this effort. License Amendment 151/150 for Vogtle Units 3 and 4 approved removal of two FPOTs and one F3POT, including the RVI CVAP test (ADAMS Accession No. ML18351A342). The Vogtle licensee later requested amendments to remove additional FPOTs and F3POTs. These were approved in License Amendments 165/163, 169/167, 171/169 (ADAMS Accession Nos. ML19262F859, ML19322C321, ML19339H316, respectively).

4. Issues and Opportunities Identified During Startup Testing in China

4.1 Sanmen Unit 1 Safety-related Pipe Vibration (NNSA and Designer)

During startup of Sanmen Unit 1, the designer and NNSA observed that the piping vibration issues that were identified during HFT had not fully been addressed. Retorqueing fasteners addressed the concern. The vibration was reduced extensively by the modifications, but it was determined that the safety-related system should be regularly monitored during outages as part of maintenance.

4.2 Sanmen Units 1 and 2 Rod Concerns (NNSA)

During operation of both Sanmen Units 1 and 2, NNSA identified concerns with the control rod control in that deviations in the rod overlap counter occurred intermittently. The designer found that the deviations occurred as a result of the related M bank not reaching the top of the core (264 step) or the bottom of the core (0 step). The designer made minor modifications to the control system logic to address the concern.

4.3 Sanmen Unit 1 Main Control Room (MCR) Abnormal Noise (NNSA and Designer)

Operators identified elevated noise levels and some vibration in the MCR as the plant increased power plateau during power ascension testing. When power was lowered, the noise disappeared. The designer found that this was due to flow through the steam lines transmitted through building structures. The designer confirmed that the piping vibration was well below limits and identified when the noise levels were of concern. Once at full power, noise levels were found to be in compliance with the regulations. An improvement initiative to further reduce MCR noise will be considered in the future for the Chinese plants. License Amendment 159/157 (ADAMS Accession No. ML19063A886, which relocated the power operated relief valve (PORV) branch lines upstream of the main steam safety valves and changed the PORV block valves from gate valves to globe valves, was approved for Vogtle Units 3 and 4 (plants under construction at the time) to address the noise concerns.

4.4 Sanmen Unit 2 Class 1E Direct Current (dc) Power and Uninterruptible Power System (IDS) Concerns (NNSA)

When Sanmen Unit 2 operators followed their procedures to operate the IDS, power was lost, leading to actuation of safety features for the system. Through later analysis, the licensee found that this was due to a problem with the procedure that led to the dc bus loss of power. The licensee revised the related procedure and trained the operators on the changes to address the concern.

4.5 Sanmen Unit 1 Diverse Actuation System (DAS) Pressurizer Automatic Actuation CMT Function Inoperable (NNSA)

During startup of Sanmen Unit 1, operators found that the pressurizer low level actuation for the CMT function for DAS Unit 1 was inoperable, as there was an outstanding engineering change to modify the scale of related instruments that had not been implemented. The DAS pressurizer level was calibrated on the cold hydro based on the original design. The DAS pressurizer level should have been recalibrated to account for the actual density of the borated water and steam in the pressurizer at different modes. The licensee plans to re-calibrate the scaling in the DAS from cold hydro to hot. Once this engineering change is implemented, the pressurizer low level actuate CMT function will be operable during a design basis event.

4.6 Sanmen Units 1 and 2 CMT Sampling Out of Band (NNSA and Designer)

The CMT boron concentrations were found to be below Technical Specification (TS) limits (TS Surveillance 3.5.2.5) during the Sanmen Unit 1 seven-day surveillance. Minor system issues were identified, and the TS limit did not allow enough margin for operation. The minor system issues were fixed, and the TS limit modified to allow conservative margin. Follow-on units adopted the modifications as preventative measures.

4.7 Ultrasonic Flow Meter (UFM) Issues (Designer)

During the initial commissioning of the feedwater UFM at Sanmen Unit 1, the UFMs did not work properly. This was addressed by adjusting the cabling. This eliminated the issues.

4.8 Feedwater Regulating Valves Open Following Reactor Trip (NRC)

During the plant shutdown from the Remote Shutdown Workstation at Sanmen Unit 2, the feedwater regulating valves did not respond as expected resulting in isolation of feedwater. The operations crew responded promptly and restored the unit to a stable condition using the RSW controls and were able to successfully complete the test. The designer was to determine the cause of the control system failure. NRC noted that this was something for regulators to observe in future unit startup tests.

5. Lessons Learnt

This section reflects lessons learnt from the perspectives of the regulators.

a) Selecting the HFT procedures to inspect according to factors such as safety importance, FPOT or F3POT tests, AP1000 special test, etc. helps focus inspection resources on the most important and safety significant tests.

b) Involving both inspectors and technical experts in the HFT test inspections, including test selection, inspection procedures preparation, test inspections and test result evaluations, helps verify that test results are in accordance with the safety analysis.

c) Involving inspectors with the licensee's HFT preparation and communication with commissioning engineers can help the inspectors to be familiar with the test process and to facilitate the monitoring of the licensees' test preparations.

d) Tracking design changes and evaluating their impact on the test procedures, including the completed tests helps ensure that design and safety requirements are met.

e) Reviewing test procedures and discussing risks and potential hazards prior to the test helps ensure protection of personnel and equipment.

f) Inspectors can better understand the acceptability of the test if, prior to the test, they ensure they understand the basis for the acceptance criteria of test results. If the acceptance criteria are unavailable prior to the test, the regulator should ensure that the designer provides the basis for acceptability after the test.

g) Regulatory cooperation and inspector exchange programs are mutually beneficial for training and knowledge transfer.

6. Recommendations

a) The regulator should communicate regularly with the licensee and vendor during planning, implementation and evaluation of tests and results to ensure a common understanding.

b) The regulator should consider conducting advanced preparatory discussion or "table-top exercises" with the licensees and/or vendors to better understand the licensee's test procedures and to allow inspectors to exercise inspection procedures. This could result in enhancements to inspection procedures and improve clarity in communications and expectations with licensees.

c) Inspectors should request that the licensees submit final test procedures to the regulator as early as possible. It is also important for the procedures to have clearly defined acceptance criteria to ensure the adequacy of the tests.

d) For those test acceptance criteria relevant to the safety analysis, inspectors should ensure licensees provide the safety basis. This is particularly important in case the test results do not meet the acceptance criteria.

e) Inspectors should compare the differences between the actual test conditions and the safety analysis postulated conditions to evaluate whether the acceptance criteria are appropriate.

f) Inspectors should focus on test procedures, specifically to ensure that the acceptance criteria meet the criteria in the commissioning program and safety analysis report.

7. References

AP1000 Design Control Document, Revision 19, 13 June 2011, Westinghouse Electric Company, USNRC ADAMS Accession No. ML11171A500.

Vogtle Electric Generating Plant, Units 3 and 4, Issuance of License Amendment No. 151 and 150 and Exemptions, Crediting Previously Completed First Plant and First Three Plant Tests (LAR 18-019), 22 January 2019, USNRC ADAMS Accession No. ML18351A342.

Westinghouse Electric Company, Technical Report WCAP-17938, Revision 3, "AP1000 In-Containment Cables and Non-Metallic Insulation Debris Integrated Assessment," USNRC ADAMS Accession No. ML18121A237.

Vogtle Electric Generating Plant, Units 3 and 4, Issuance of License Amendment No. 62 and Exemptions, ADS Valve Flow Area Changes (LAR 16-012), 29 December 2016, USNRC ADAMS Accession No. ML16357A640.

Vogtle Electric Generating Plant, Units 3 and 4, Issuance of License Amendment Nos. 159 and 157 and Exemptions, Power Operated Relief Valve Noise Mitigation (LAR 18-021), 18 April 2019, USNRC ADAMS Accession No. ML19063A886.