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Qualification testing of PWR fuel assemblies at ABB

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ABSTRACT

Hydraulic qualification testing of improved fuel designs is receiving considerable attention because of the emphasis the nuclear industry places on fuel reliability and because of an increased percentage of fuel failures due to grid-to-rod fretting as failures from other causes are eliminated. The objective of the hydraulic qualification testing is to demonstrate compatibility of the newer design with the resident fuel and to demonstrate that the fretting performance of the improved design is comparable or superior to that of a current design with proven performance. Because of the complex interactions involved in grid-to-rod fretting, the hydraulic testing must closely simulate the in-core conditions that exist throughout the design life of the fuel. This paper presents the design and typical results of the hydraulic qualification testing performed on recent, improved ABB fuel designs.

INTRODUCTION

The top priority of ABB's PWR fuel customers is fuel reliability. Prior to introducing an improved fuel design, an extensive qualification program is performed using ABB's proven product development process. Hydraulic qualification testing of the full scale fuel assembly is integral to the qualification program. Hydraulic qualification testing is used to verify that the improved design meets acceptance criteria for assembly pressure drop and grid-to-rod fretting performance. This paper discusses the qualification test design and results for the most recent ABB fuel qualification test programs.

TEST DESIGN

The hydraulic qualification testing for ABB fuel designs includes a single bundle pressure drop test, a single bundle flow sweep vibration test, and a single or dual bundle endurance test. Because of the complex interactions involved in assembly vibration and grid-to-rod fretting, hydraulic testing is designed to closely simulate in-core conditions that exist throughout the design life of the fuel. Therefore, all tests are designed to duplicate conditions encountered by the fuel from startup through full power operation. The tests are performed with a full scale prototype fuel assembly that is loaded with depleted uranium rods to match the vibrational characteristics and geometry of the fuel rods. The tests are performed with simulated reactor support plate geometries and are conducted in qualified test facilities, predominately ABB's Test Facility 2 (TF-2) located in Windsor, Connecticut. A description of the test facility and the design of the each qualification test are provided below.

Test Facility

Qualification tests on full scale prototype fuel designs are performed in ABB CE's TF-2 test facility, shown schematically in Figure 1. The TF-2 test loop is an out-of-pile test facility used to verify the mechanical and hydraulic characteristics of ABB fuel assembly prototypes. The loop is constructed of stainless steel and is designed for flow rates up to 3,400 m^3/h, temperatures up to 343°C, and pressures up to 17.24 MPa. The loop has two test sections. The main test section can accommodate up to five full-size fuel assemblies. The bypass section is sized for single fuel bundle testing. Heat is provided for both sections by a single stage pump that can be operated at two speeds.

Recent qualification testing (since 1990) of various fuel designs has been performed in the main test section because of its added stability when investigating fuel assembly vibration phenomena. Tests are performed using special, heavy wall single or dual bundle shrouds. Flow from the loop passes from the pump through several flow straightener sections, into the shroud and test fuel assembly, and finally through a calibrated, internal flow meter section before it exits the test vessel and is returned to the test loop.

Pressure Drop Test

A single bundle pressure drop test is performed on the prototype assembly to determine the assembly and component loss coefficients over a range of operating conditions from cold startup to full power operation. Test data are obtained over a range of bare rod Reynolds numbers from approximately 70,000 to over 500,000. To obtain reliable data over this range, the test data are acquired at test conditions ranging from 66°C and 2.6 MPa to 321°C and 15.5 MPa. As the test loop temperature and pressure conditions are varied, the selected test matrix points provide overlapping data as a function of bare rod Reynolds number. To ensure the data are obtained at equilibrium conditions, the loop is operated for a minimum of one hour at each specified temperature condition prior to acquiring the data. The pressure drop data are recorded across the assembly and components using wall taps positioned on opposite sides of the test shroud to minimize any impact of the assembly position within the shroud. The surface roughness on the shroud wall is comparable to the fuel rod surface roughness. The single bundle test shroud is sized to provide measured spacer grid loss coefficients directly applicable for in-reactor hydraulic analyses. The data acquisition program controls two high pressure multi-port scanning valves to obtain a direct measure of each specified differential pressure. The differential pressures are recorded using up to four pressure transmitters for redundancy and to minimize instrument related biases. The results are processed almost real time using special spreadsheet templates and compared to predictions before proceeding to the next step.

Flow Sweep Test

Fuel assembly motions are monitored during single bundle tests with non-intrusive proximity transducers mounted in the test shroud. During the pressure drop test, vibration data are recorded over a wide range of flow and pressure/temperature conditions encountered by the fuel from startup through full power operation. In addition, a flow sweep test is performed with the flow varied from 75% to 120% of best estimate reactor flow in 11 to 22 m^3/h increments at core average temperature to determine whether the fuel designs are susceptible to flow induced fuel assembly vibrations, as observed in testing by other vendors, Reference [1]. The proximity transducers are placed at three grid elevations to allow investigation of assembly motions at multiple assembly vibration modes.

Endurance Test

A single or dual assembly endurance test is performed in the TF-2 loop following the single assembly pressure drop and flow sweep tests to demonstrate that the fretting performance of the new design is comparable or superior to that of a design with proven performance. Previous testing in TF-2 and elsewhere has shown that fretting wear is a function of many parameters including grid-to-rod gap size, axial velocity, crossflow velocity, grid span length, rod and grid materials, rod oxide thickness, grid contact geometry, and test duration. These parameters need to be considered in the design of the endurance test.

To closely simulate in-reactor conditions that exist throughout the design life of the fuel, the endurance test is performed on a prototype fuel assembly with prototype grids and rods filled with depleted uranium pellets. A dual bundle endurance test is performed when the loss coefficient differs from co-resident fuel by more than 10% for individual spacer grids and/or by more than 5% for the assembly. Such a dual bundle endurance test is performed with assembly "A" matching the hydraulic resistance of the co-resident fuel adjacent to assembly "B", the prototype of the new design, to demonstrate acceptable performance for both assemblies in transition cores with the maximum crossflow velocities. Pressure drop data are taken over a range of operating conditions for the dual bundle endurance test to determine average axial flow splits from cold startup to full power operation. Fuel assembly vibration data on both assemblies are monitored to determine vibration levels of assemblies over the previously specified operational range.

The single and/or dual assembly endurance test is performed at the Mechanical Design maximum flow, core exit temperature and operating pressure, unless assembly vibration resonance is observed at other operational conditions during the flow sweep test. The test is performed in excess of 500 hours at these operating temperature and pressure conditions to best match the assembly and rod vibrational and damping characteristics in the reactor. Since zircaloy is a "soft" metal, the wear at 316°C is of the adhesive type, Figure 2, rather than of the abrasive wear observed at lower temperatures. In addition, recent testing indicates that rod wear is lower (both frequency and depth) at temperatures of 150°C compared to results at 316°C. The oxide layer on test rods that are loaded into cells that simulate Middle of Life (MOL) or End of Life (EOL) conditions have an oxide layer of 1 to 1.5 µm because the rods in a reactor would have more than 1.5 µm of oxide after one cycle of operation. The oxide thickness on the rod is an important wear parameter since, based upon results from several tests performed in TF-2, the maximum wear depth for large gaps is a strong function of oxide thickness, Figure 3.

The endurance test is performed with grid cells for a minimum of 50 rods set at each of three conditions, minimum cell size (beginning of life (BOL) or zero gap), best estimate rod to grid support gap near MOL, and maximum cell size (EOL or maximum credible rod to grid support gap). The number of cells is selected to obtain results with an adequate sample size because, without measurable assembly vibration, previous endurance test data indicate that measurable wear is found on only a small percentage (~10%) of rods in grid cells set with large gaps. Grid cell settings on the test assembly or assemblies are measured within 12.7 μm with 100% inspection prior to the test. The rod diameters are also measured prior to the test to determine the as-built gaps between the rod and the grid cell rod support features.

APPLICATION OF TEST RESULTS

Pressure Drop Test

The objective of the pressure drop test is to determine the loss coefficients across individual zircaloy spacer grids, for the assembly entrance region including the support plate, bottom nozzle, and bottom grid, for the assembly exit region including the top grid, the top nozzle and the upper support plate, and for the overall assembly. The entrance and exit region loss coefficients are separated into individual component loss coefficients by ancillary analysis. A plot of the measured grid and assembly loss coefficients for a recent qualification test is shown in Figure 4. The test data are curve fit with the expression, $K = A + B*Re^{-0.20}$, where Re is the Reynolds number in the bare rod region of the core. The coefficient A is the form loss component and the term $B*Re^{-0.20}$ represents the friction loss component of the overall grid or assembly loss coefficient. The grid loss coefficient is based upon the average value for a minimum of four grids. Data are recorded across single and multiple grid spans to check for consistency of the measurements. The assembly loss coefficient is determined by an overall measurement and is verified against the sum of component measurements. The loss coefficient results are used in mixed core thermal hydraulic analyses, assembly uplift evaluations, and to confirm the determination, based upon analytical models, of the selection of either single or dual assembly endurance testing.

Pressure drop data are also recorded during the endurance test to ensure that conditions are maintained throughout the test. During dual bundle endurance tests, the pressure drop is measured across each assembly separately in order to determine the flow split. This is accomplished by using the measured component pressure drops and the single bundle loss coefficients. The measured flow split is compared to the predicted flow split, using the measured loss coefficient data, and ABB's thermal-hydraulic code TORC, as shown in Figure 5, to demonstrate the adequacy of the T-H prediction methods for mixed cores.

Flow Sweep Test

The objective of the flow sweep test is to determine if there is an assembly resonance over the entire range of flows at reactor operating temperatures and pressures. Proximity displacement data are processed both on-line and off-line to track grid locations with respect to shroud walls, so as to provide time histories and orbital motion displays for visualization of general motion behavior, and to express vibration amplitudes in terms of RMS and RSS values for each monitoring elevation. Also, spectral graphs are created to permit identification of significant response frequencies and modal response behavior.

Fuel assembly vibration data from recent qualification tests have varied from case to case, mostly displaying stochastic responses and occasionally some low frequency deterministic responses. However, in all tests to date, vibration levels remained acceptable, sometimes as low a 12.5 μm RSS over the entire flow sweep ranges and temperature/pressure variations.

The time history and orbital collage of Figure 6 reflects narrow and broad band random vibration behavior. The characteristics of these time histories changed only slightly with temperature and flow. The relative and absolute orbital motion graphs on the right hand side of Figure 6 further illustrate the low level of fuel assembly vibration, especially when viewed with respect of the available shroud clearances. The RSS vibration amplitudes as a function of flow, from a recent flow sweep test, are shown in Figure 7.

Assembly vibration data are also recorded during the endurance test. For dual bundle endurance tests, both assemblies are monitored over a range of temperature and flow conditions, as well as throughout the entire endurance test to determine assembly vibrational behavior in the presence of crossflow. No significant changes have been observed in the RSS vibration amplitudes in the dual bundle tests from those observed in the single bundle test, Figure 7.

Endurance Test

The objective of the endurance test program is to demonstrate that the fretting-related performance of the new fuel design falls within that of a proven fuel design. Since the rod wear is a function of several test parameters, the observed wear has to be compared to an acceptance criterion based upon data for a proven design taken at comparable conditions. Following the endurance test, all rods are examined for evidence of wear and the locations and actual depths of all observable wear are determined. The magnitude, frequency, and location of wear as a function of rod to grid support gap size (nominal, best estimate, and worst credible end of life) are compared to an acceptance criterion based upon TF-2 data for a proven fuel design, Figure 8. The wear data for the new design should not be greater than the acceptance criterion.

CONCLUSIONS

Extensive qualification testing is performed by ABB to demonstrate the acceptable performance of new fuel assembly designs. The prototypical test assemblies simulate rod support geometry and flow, pressure and temperature conditions that exist over the entire life time of the fuel in a core. Pressure drop results are compared to expected thermo-hydraulic performance parameters: flow sweep tests are used to demonstrate adequate resistance to flow induced assembly vibrations; endurance tests provide fuel rod wear performance data that are compared with previous wear test programs and that can be linked to the well established wear resistance of fuel designs ascertained from inspections performed over the past two decades of fuel assemblies at operating plants.

REFERENCES

1. Miller, R. S., Moon, J. E., Stanutz, R. N., Kunishi, H., Wilson, H. W., and Wood III, J. D., "Westinghouse Fuel Operating at High Burnup and with Advanced Features", 1994 International Topical Meeting on LWR Fuel Performance, Orlando, Florida, April 17-24, 1994.

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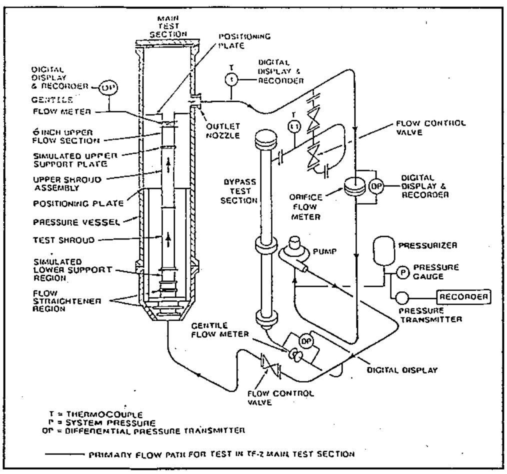

Figure 1: TF-2 Facility Layout

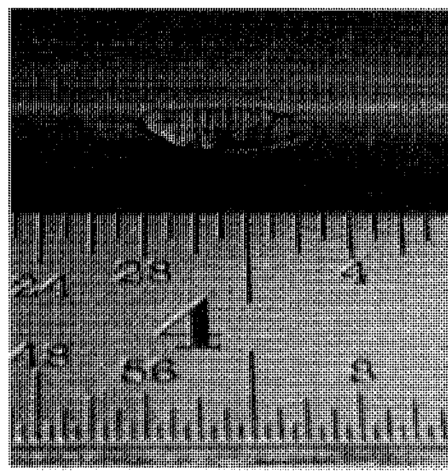

Figure 2: Fuel Rod Wear Scar

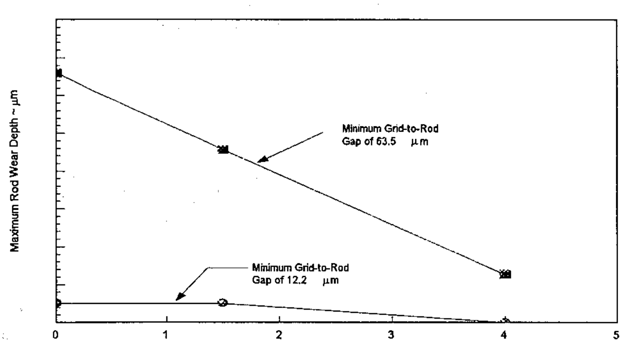

Figure 3: Maximum Rod Wear Depth vs. Rod Oxide Thickness
TF-2 - Pre-Oxidized Rods, Bare Rod Velocity
Approximately 5.75 m/s

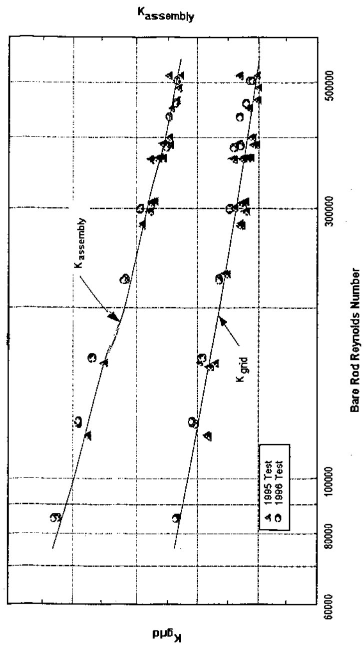

Figure 4: TF-2 Hydraulic Pressure Drop Test Program Kgrid and Kassembly vs. Bare Rod Reynolds Number

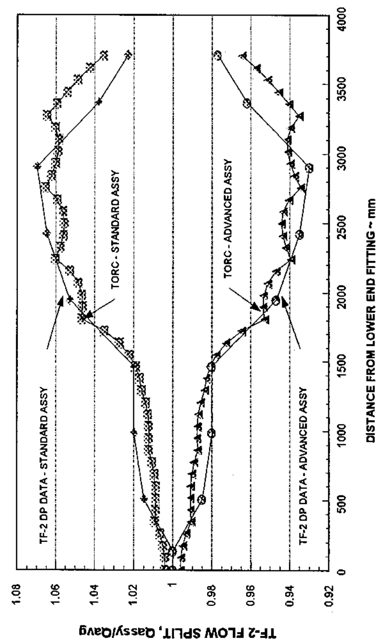

Figure 5: Comparison of Measured and Predicted Normalized Assembly Flow

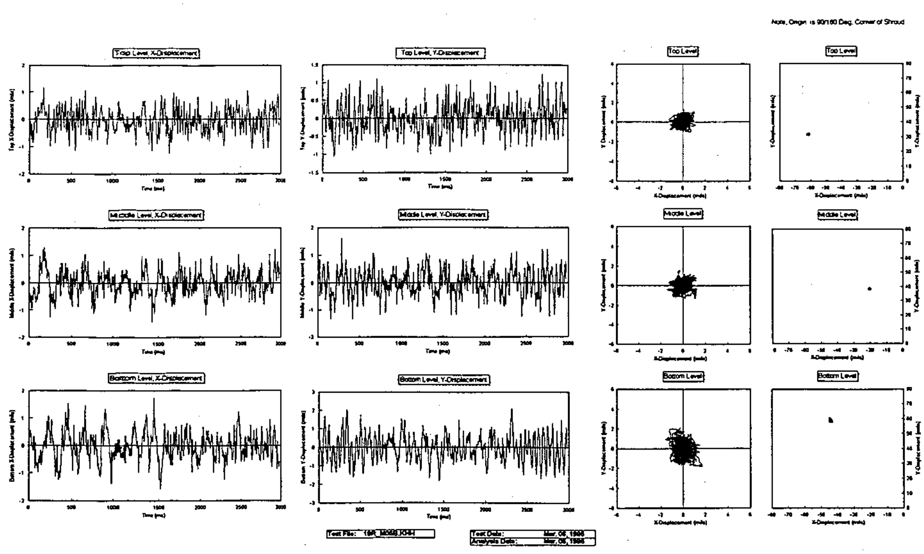

Figure 6: Biaxial Time Histories and Orbital Displays for Three Grid Elevations (1 mil≡25 μm)

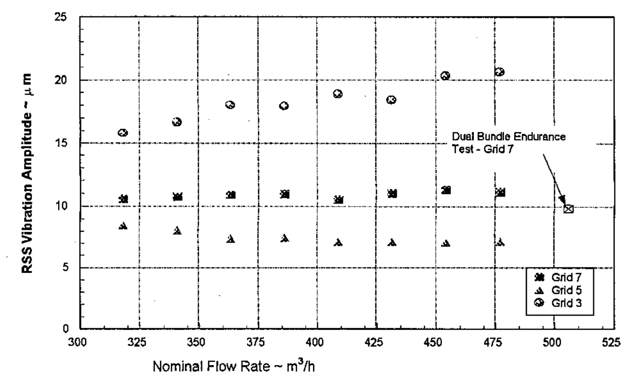

Figure 7: Assembly RSS Vibration Results, Single Bundle Flow Sweep and Dual Bundle Endurance Test

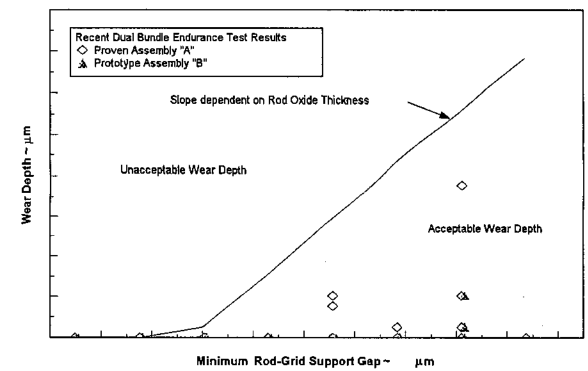

Figure 8: TF-2 Endurance Test Wear Depth Criterion Temperature - 600°F, Zircaloy-4 Rods

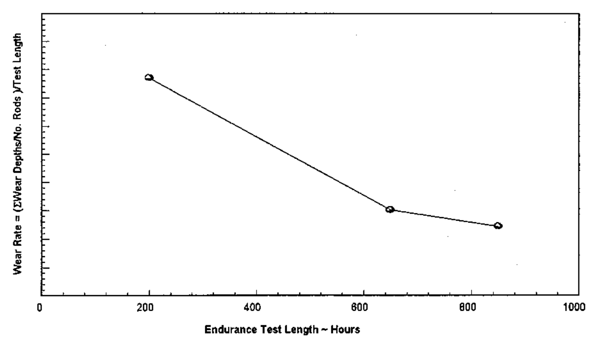

Figure 9: TF-2 Endurance Tests, Rod Wear Rate vs. Time for Given Rod-to-Grid Gap Size