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PLUS7^{TM} EOL GRID AND FUEL ASSEMBLY TESTS

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ABSTRACT: *KNF jointly developed PLUS7^{TM} fuel design from 1999 to 2002 with Westinghouse to improve the fuel performance relative to previous fuel design. Based on the successful in-reactor performance of the LTAs and CSAs, more than 5,000 PLUS7^{TM} fuel assemblies have been supplied since 2006 with excellent in-reactor performance. The fuel assembly structural evaluation for the seismic and LOCA loads was performed for the BOL(Beginning of Life) condition based on the SRP(Standard Review Plan) 4.2 Appendix A. In SRP 4.2 Appendix A, it is assumed that increase in yield and ultimate strength due to irradiation offset the EOL(End of Life) effects on grid strength. In June 2012, the NRC issued Information Notice 2012-09 which challenges the previous assumption based on experience. In this paper, the details of PLUS7^{TM} EOL grid and fuel assembly mechanical and hydraulic tests are described. The EOL grid cell sizes are determined considering irradiation induced spring relaxation, grid growth and cladding creep-down. The EOL conditions are simulated by increasing the cell sizes. A series of grid crush tests and fuel assembly mechanical and hydraulic tests were performed to get the EOL characteristics of PLUS7^{TM} grid and fuel assembly. The EOL grid and fuel assembly mechanical and hydraulic test results will be used for the EOL fuel assembly seismic and LOCA analysis.*

KEYWORDS: *PLUS7^{TM}, BOL, EOL, Static Compression Test, One-Sided Impact Test, Thru-Grid Impact Test, Fuel Assembly Mechanical Test, Flowing Water Damping Coefficient*

I. INTRODUCTION

KEPCO Nuclear Fuel (KNF) jointly developed PLUS7^{TM} fuel design from 1999 to 2002 with Westinghouse to improve the fuel performance relative to previous fuel design. Four Lead Test Assemblies (LTAs) were loaded in Hanul Unit 3 (OPR1000 NPP) and irradiated for three cycles from 2002 to 2007. It was confirmed that the LTAs were irradiated within the design limits through the pool-side examinations at the end of each cycle. Additionally, four Commercial Surveillance Assemblies (CSAs) were examined in Hanbit Unit 5 for three cycles from 2006 to 2010. The in-pile performance of PLUS7^{TM} fuel design was confirmed through the LTAs and CSAs. Based on the successful in-reactor performance of the LTAs and CSAs, more than 5,000 PLUS7^{TM} fuel assemblies have been supplied since 2006 with excellent in-reactor performance.

The PLUS7^{TM} fuel assembly is a 16x16 type assembly with 236 fuel rods, and 150 inch fuel stack length. The assembly contains ZIRLO^{TM} clad fuel rods that have an outer diameter of 0.374 inches. The structural skeleton is comprised of four guide tubes and one center instrumentation tube. At the lower end of the assembly, there is a bottom nozzle with small holes to enhance the debris-filtering efficiency. Then, an Inconel 718 bottom grid with high burnup capability is utilized. Nine ZIRLO^{TM} mid-grids with mixing vanes are utilized, followed at the very top of the assembly by an Inconel 718 vaneless structural grid. The top nozzle is designed to have a removable attachment feature. The fuel stack is contained within the fuel tube, which is charged and pressurized with helium. There is a plenum at the top, and a variable pitch plenum spring is used.[1]

The fuel assembly structural evaluation for the seismic and LOCA loads was performed for the BOL(Beginning of Life) condition based on the SRP(Standard Review Plan) 4.2 Appendix A. In SRP 4.2 Appendix A, it is assumed that increase in yield and ultimate strength due to irradiation offset the EOL(End of Life) effects on grid strength.[2] In June 2012, the NRC issued Information Notice 2012-09 which challenges the previous assumption based on experience.[3] The relaxation of grid springs and resulting gap between fuel rod and grid support feature may lower the grid crush strength and fuel assembly stiffness resulting in lower frequencies which may impact the dynamic model results. To evaluate the PLUS7^{TM} EOL fuel assembly structural performance for the seismic and LOCA loads, the fuel assembly mechanical test program has been launched.

In this paper, the details of PLUS7^{TM} EOL grid and fuel assembly mechanical and hydraulic tests are described. The EOL grid cell sizes are determined considering irradiation induced spring relaxation, grid growth and cladding creep-down. The EOL conditions are simulated by increasing the grid cell sizes. A series of grid crush tests and fuel assembly mechanical and hydraulic tests were performed to get the EOL characteristics of PLUS7^{TM} grid and fuel assembly. The EOL grid and fuel assembly mechanical and hydraulic test results will be used for the EOL fuel assembly seismic and LOCA analysis.

II. PLUS7^{TM} EOL GRID AND ASSEMBLY TESTS

Due to the irradiation effects, the fuel assembly natural frequencies and grid crush strength can be reduced at End of Life (EOL) condition. NRC issued IN 2012-09 in June 2012 which challenged approved assumptions based on Beginning of Life (BOL) in seismic and Loss of Coolant Accident (LOCA) analysis. By using fuel assembly flowing water damping (higher damping value), the margin lost due to EOL condition can be regained. This approach was accepted for a prior submission to the NRC.[4] To evaluate the EOL seismic performance of the fuel assembly, simulated EOL grids, skeleton and fuel assemblies were manufactured. The EOL grid cell size were determined based on the measured data for the irradiated grids of PLUS7^{TM} fuel assembly. The cell size of the BOL grids were adjusted to manufacture the simulated EOL grids.[5]

II.A. PLUS7^{TM} EOL GRID TEST

The EOL grid tests were performed using simulated EOL grids to generate static and dynamic characteristics of the EOL grids for seismic and LOCA analysis. All of the grid tests were performed at room temperature in air condition. The static compression tests were performed to generate the static stiffness and static buckling load of EOL grids. The compression load was applied on the grid for the static compression test. The dynamic impact tests were performed to generate dynamic stiffness and dynamic buckling load. The one-sided drop tests were performed to determine the one-sided crush strength and coefficient of restitution. Vertical one-sided impacts of grids were simulated using a grid span section of a fuel assembly for the one-sided drop test. The through-grid long pulse tests were performed to determine the through-grid crush strength. The load pulse was applied to the grid span section of fuel assembly for the through-grid long pulse tests.

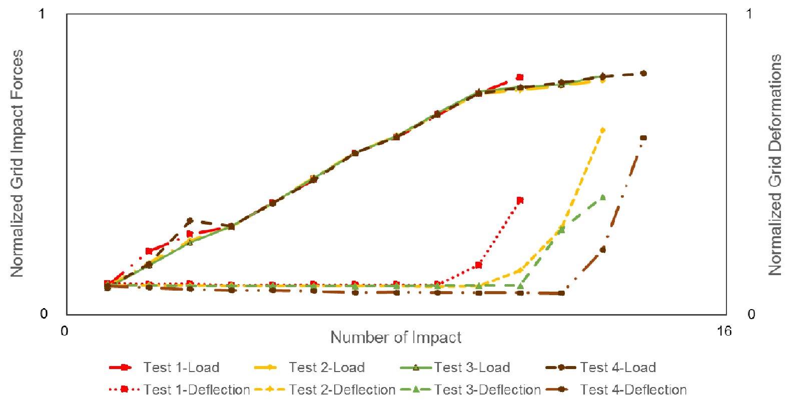

Fig. 1. Normalized Grid Impact Forces and Deformations

Fig. 1 shows the normalized grid impact forces and deformations for through-grid long pulse tests. Based on the test results, it is confirmed that the EOL crush strength are reduced compared with the BOL crush strength because of the increased grid cell size. The static stiffness, one-sided crush strength and coefficient of restitution, and the through-grid crush strength of the grids will be used for the EOL fuel assembly seismic and LOCA analysis.

II.B. PLUS7^{TM} EOL ASSEMBLY MECHANICAL TEST

The EOL fuel assembly mechanical tests were performed using a simulated EOL fuel assembly to generate fuel assembly static load-deflection characteristics, natural frequencies, mode shapes and impact characteristics. The fuel assembly was positioned vertically in the test stand and restrained at the top and bottom nozzles with core plate simulators for the typical reactor support conditions. The fuel assembly was axially pre-loaded to approximate the in-core condition. The fuel assembly lateral stiffness test was performed to determine the lateral load-deflection characteristics of the PLUS7^{TM} fuel assembly. The fuel assembly lateral vibration test was performed to obtain the PLUS7^{TM} fuel assembly natural frequencies and mode shapes, and to determine the fuel assembly structural damping. The forced vibration test and pluck vibration test were performed to obtain the fundamental frequencies and mode shapes of the fuel assembly. The fuel assembly lateral impact test was performed to determine the PLUS7^{TM} fuel assembly impact characteristics with the top and bottom nozzles constrained within core boundary conditions. The test was designed to simulate assembly to core shroud impact by allowing the mid-grids to impact rigid plates. Fig. 2 shows the fuel assembly deflection shapes for several lateral deflections. Based on the test results, it is confirmed that the most of fuel assembly EOL characteristics are similar with the fuel assembly BOL characteristics except the natural frequency of the fuel assembly. The natural frequency of the EOL fuel assembly was lower than that of BOL fuel assembly because of the reduced fuel assembly lateral stiffness. The fuel assembly test results will be used to verify the static and dynamic characteristics of the fuel assembly finite element models for the EOL fuel assembly seismic and LOCA analysis.

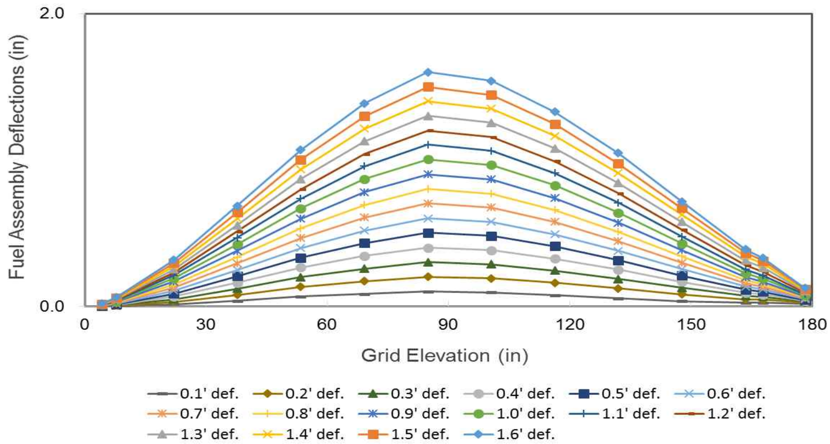

Fig. 2. Fuel Assembly Deflection Shapes

II.C. PLUS7^{TM} EOL ASSEMBLY DAMPING TEST

The EOL fuel assembly damping tests were performed using a simulated EOL fuel assembly to generate fuel assembly damping coefficient. The fuel assembly was positioned vertically in a closed isothermal hydraulic loop and restrained at the top and bottom nozzles with core plate simulators. The in air pluck test was performed to determine the natural frequency of the PLUS7^{TM} fuel assembly in air condition. After the in air test, the still water and flowing water tests were performed to generate the fuel assembly damping coefficient for still water and flowing water conditions. The still water tests were performed for several temperatures and displacements and the flowing water tests were performed for several temperatures, velocities and displacements. The still water test data were evaluated to determine the natural frequency and damping coefficient of the PLUS7™ fuel assembly in still water condition. The flowing water test data were evaluated to determine the damping coefficient of the PLUS7™ fuel assembly in flowing water condition. Fig. 3 shows the normalized damping coefficients vs. amplitudes for still water and flowing water conditions at high temperature. Based on the test results, it is confirmed that the fuel assembly damping in still water and flowing water is not sensitive to vibration amplitude and strongly dependent on the flow velocity. The still water and flowing water damping test results of the PLUS7™ fuel assembly will be used for the EOL fuel assembly seismic and LOCA analysis.

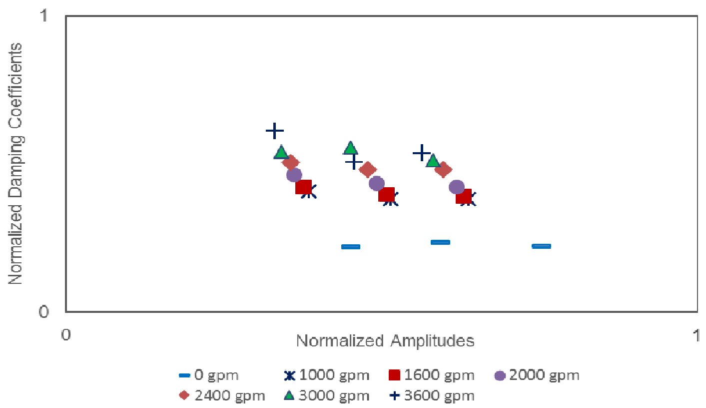

Fig. 3. Normalized Damping Coefficients vs. Amplitudes at High Temperature

III. CONCLUSIONS

To evaluate the EOL seismic performance of the fuel assembly, simulated EOL grids, skeleton and fuel assemblies were manufactured. The EOL grid cell sizes are determined considering irradiation induced spring relaxation, grid growth and cladding creep-down. The EOL conditions are simulated by increasing the cell sizes. A series of grid crush tests and fuel assembly mechanical and hydraulic tests were performed to get the EOL characteristics of PLUS7™ grid and fuel assembly.

Based on the test results, the EOL crush strength are reduced compared with the BOL crush strength because of the increased grid cell size. The most of fuel assembly EOL characteristics are similar with the fuel assembly BOL characteristics except the natural frequency of the fuel assembly. The natural frequency of the EOL fuel assembly was lower than that of BOL fuel assembly because of the reduced fuel assembly lateral stiffness. The fuel assembly damping in still water and flowing water is not sensitive to vibration amplitude and strongly dependent on the flow velocity. The EOL grid and fuel assembly mechanical and hydraulic test results will be used to generate the fuel assembly models for the EOL fuel assembly seismic and LOCA analysis.

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