Transactions of the Korean Nuclear Society Spring Meeting
Jeju, Korea, May 7-8, 2015

Assembly Bow Characteristics of the HIPER16^{TM} Fuel Design

Sang-Youn Jeon*, O-Cheol Kwon, Dong-Geun Ha, Jae-Ik Kim
KEPCO Nuclear Fuel Co., Ltd, Nuclear Fuel Technology Dept.
242, Daedeok-daero 989beon-gil, Yuseong-gu, Daejeon, 305-353, Korea
** Corresponding author : syjeon@knfc.co.kr*

1. Introduction

KEPCO Nuclear Fuel (KNF) developed the HIPER16^{TM} (High Performance with Efficiency and Reliability) fuel design in 2010, accomplishing a series of out-of-pile tests[1]. The out-of-pile tests were performed either in air or in a hydraulic loop and at room temperature or operating temperature conditions. The test results include the required physical and thermal-hydraulic data needed to verify the HIPER16^{TM} fuel design. The mechanical integrity and safety of HIPER16^{TM} fuel design has been verified based on the final verification tests and evaluations.

The HIPER16^{TM} Lead Test Assemblies (LTAs) were loaded in HANUL Unit 6 for 3 cycles from 2011 to 2015. The four ZIRLO^{TM} LTAs and the other four HANA^{TM} LTAs were loaded in symmetric positions in the core and located at the vicinity of the shroud during 1st irradiation cycle of LTA. The poolside examinations have been performed after 1st and 2nd irradiation cycle of LTA to verify the in-reactor performance of HIPER16^{TM} fuel design. The visual examinations and dimensional measurements were performed on the LTAs using poolside examination equipment. The in-reactor verification test results showed that the HIPER16^{TM} fuel design met the irradiation related design requirement. The poolside examinations after 3rd irradiation cycle of LTA will be performed in the end of 2015.

In this study, the fuel assembly bow characteristics of the HIPER16^{TM} fuel design have been investigated by analyzing the measured fuel assembly bow data after 1st and 2nd irradiation cycle of LTA.

2. HIPER16^{TM} Fuel Design Characteristics

The HIPER16^{TM} design is a 16X16 array with a 0.374 inch fuel rod design, and a 150 inch fuel stack length for CE-NSSS Type Nuclear Power Plants. Table I identifies the main design values of the HIPER16^{TM} fuel design and Fig. 1 shows the key design features of the HIPER16^{TM} fuel assembly. As indicated in Fig. 1, the HIPER16^{TM} fuel design features include: Removable Top Nozzle, Reduced Rod Bow (RRB) Inconel top grid, ZIRLO^{TM} or HANA^{TM} mid and IFM grids, high debris filtering Inconel bottom grid, low pressure drop Bottom Nozzle, SRA ZIRLO^{TM} or HANA^{TM} guide tube and instrument tubes, and fuel cladding[2].

Table I. Main Design Values of HIPER16^{TM}

Items	Values
Fuel Array	16x16
Fuel Assembly Pitch (in.)	8.180
Number of Rods per Assembly (EA)	236
Fuel Rod Pitch (in.)	0.506
Fuel Rod OD (in.)	0.374
Fuel Stack Length (in.)	150
Number of Guide Tubes (EA)	4
Guide Tubes OD (in.)	0.980
Number of instrument tubes (EA)	1
Number of MID Grids	9
Number of IFM Grids	2

The structural skeleton is comprised of four guide tubes and one center instrumentation tube with a 0.980 inch diameter. The guide tubes are quite different in respect that the uniform outer diameter guide tubes are used in the HIPER16^{TM} fuel assembly. The dashpot region is implemented using a separate dashpot tube which is spot-welded to the outer guide tube. The thickness of the guide tube and instrumentation tube is the same as that of PLUS7^{TM} fuel design.

At the lower end of the assembly, there is a low pressure drop bottom nozzle with large square holes. Then, an Inconel 718 bottom grid with debris filtering capability is utilized. Nine ZIRLO^{TM} or HANA^{TM} mid-grids with mixing vanes and two intermediate flow mixers are then utilized, followed at the very top of the assembly by an Inconel 718 vaneless structural top grid. All the grids are fabricated from slotted, interlocked straps which are attached by either laser welding or brazing. The top and bottom nozzles are fabricated from Type 304 stainless steel. The top nozzle is designed to have a removable attachment feature. The total pellet stack length is 150 inches. The fuel stack is contained within the fuel tube, which is pressurized with helium. There is a plenum at the top, and a variable pitch rod plenum spring is used for high burnup capability.

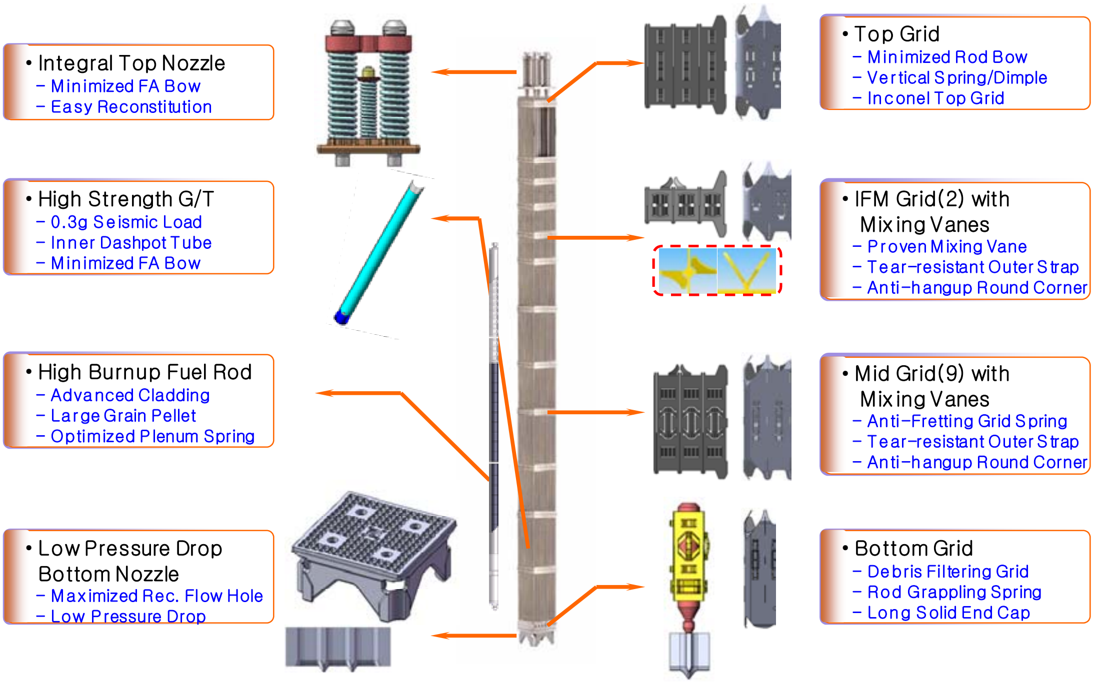


Fig. 1. Key Design Features of HIPER16^{TM}

3. Fuel Assembly Bow Characteristics

The fuel assembly bow has been widely observed in virtually all commercial Pressurized Water Reactors (PWR). The extreme level of fuel assembly bow can bring the Incomplete Rod Insertion (IRI), adverse effects on the nuclear design, or handling difficulties that affect the nuclear plant performance.

The reactor core in PWR is comprised of an array of square fuel assemblies. Each fuel assembly is installed vertically in the reactor vessel and stands upright on the lower core plate. After all fuel assemblies are set in place on the lower core plate, the upper core support structure which contains the upper core plate is installed. The upper core plate press down the fuel assembly hold-down springs to hold the fuel assemblies in place against the upward hydraulic force, putting the fuel assemblies under compressive load.

The fuel assembly length will be increased due to the irradiation growth and oxide formation, and decreased due to the creep down and elastic deformation. The hold-down spring forces will be increased as the irradiation induced growth increase. The amount of the creep down will be increased with the higher downward hold-down spring forces and upward hydraulic force.

These irradiation growths and creep downs are main parameters for the evaluation of the fuel assembly axial growth and lateral bow. The irradiation growth is defined as a change in shape without a volume change during irradiation in the absence of applied stress. The main phenomenon which can be caused by irradiation growth is the fuel assembly bow.

The fuel assembly bow is the loss of straightness caused by differential temperatures and strains between opposite faces of a fuel assembly.

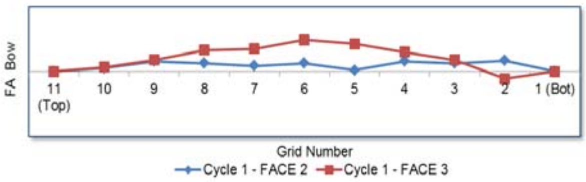
The fuel assembly and fuel rods grow during operation in reactor as a result of the cumulative effect of: oxide formation, stress free irradiation growth, stress induced irradiation creep, and elastic deformation. Due to the fuel assembly growth the compressive load of the holddown spring increases while the fuel rod growth tends to put the fuel assembly structure in tension. The amount of this load change that is applied to the guide tubes and fuel rods depends on whether the rods are slipping through the grids or not. At the beginning of life, the rods are not slipping through the grids, and then the thimbles and rods share the load change according to their relative stiffness. During operation the grid spring force relax and the rods slip through the grids, then the thimbles take the entire load change. The net compressive force on the guide thimbles is one of the primary effects to induce the fuel assembly to bow. As the distance between assemblies in the core is very small, the fuel assemblies push one another and the bow can be propagated through the core.

4. HIPER16^{TM} Fuel Assembly Bow

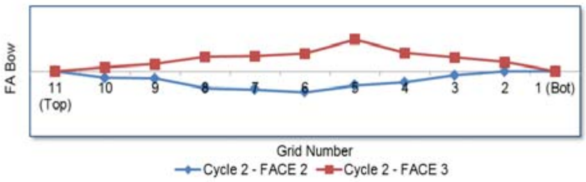
The fuel assembly bow measurements were performed for the HIPER16^{TM} fuel assemblies with ZIRLO^{TM} and HANA^{TM} material in HANUL Unit 6. The measured fuel assembly bow data for the ZIRLO^{TM} and HANA^{TM} HIPER16^{TM} fuel assemblies have been analyzed to investigate the characteristics of fuel assembly bow for the HIPER16^{TM} fuel assembly design.

Fig. 2 shows the fuel assembly bow for each face of the HIPER16™ fuel assembly with ZIRLO™ material for cycle 1 and 2. Fig. 3 shows the fuel assembly bow for each face of the HIPER16™ fuel assembly with HANA™ material for cycle 1 and 2. The typical shape of the HIPER16™ fuel assembly bow is "S" shape and the direction of fuel assembly bow was changed as the number of cycle increase. Based on the measured data and evaluation results, the bow characteristics of HIPER16™ fuel assembly design for ZIRLO™ and HANA™ material are very similar.

The fuel assembly bow requirement has been established based on the loading and unloading performance of fuel assembly in the core. The maximum values of the measured fuel assembly bow data for the HIPER16™ fuel assembly design with ZIRLO™ and HANA™ materials are about 25% of the allowable fuel assembly bow requirement.

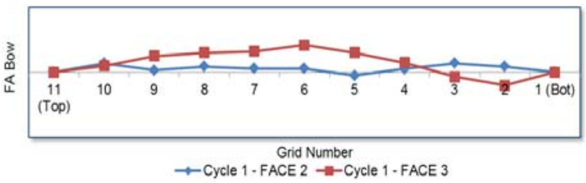


(a) Cycle 1 (Face 2 and 3)

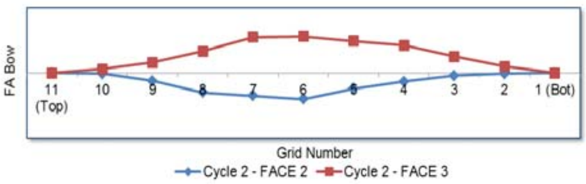


(b) Cycle 2 (Face 2 and 3)

Fig. 2 HIPER16™ Fuel Assembly Bow (ZIRLO™)



(a) Cycle 1 (Face 2 and 3)

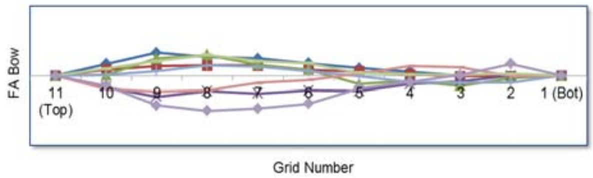


(b) Cycle 2 (Face 2 and 3)

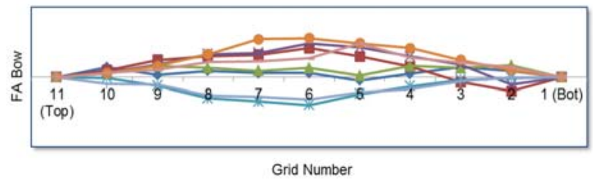
Fig. 3 HIPER16™ Fuel Assembly Bow (HANA™)

Fig. 4 shows the measured bow of PLUS7™ and HIPER16™ fuel designs[2]. There are some differences on the shape of fuel assembly bow between PLUS7™ and HIPER16™ fuel designs. The maximum fuel assembly bow occurs at the upper part of the fuel assembly for the PLUS7™ design and at the middle part of the fuel assembly for the HIPER16™ design.

The shape of the fuel assembly bow can be affected by the fuel assembly lateral stiffness distribution along the fuel assembly length. The main design parameters to increase the fuel assembly lateral stiffness are the guide thimble stiffness, fuel rod stiffness and the number of joints between guide tubes and spacer grids. The guide thimble stiffness and fuel rod stiffness of HIPER16™ fuel design are almost same as that of PLUS7™ fuel design. There are two IFM grids at the upper part of the HIPER16™ fuel assembly. The two IFM grids at the upper part of the HIPER16™ fuel assembly increase the lateral stiffness of the HIPER16™ at the upper part of the fuel assembly due to the additional joints between guide tubes and spacer grids. Based on the evaluation results, it seems that the differences of the fuel assembly bow shape are mainly due to the two IFM grids of HIPER16™ fuel design. The maximum fuel assembly bow of PLUS7™ and HIPER16™ fuel designs are almost same regardless of the location of maximum fuel assembly bow.



(a) PLUS7™ (Cycle 1~2, ZIRLO™)



(b) HIPER16™ (Cycle 1~2, ZIRLO™/HANA™)

Fig. 4 Fuel Assembly Bow (PLUS7™ vs. HIPER16™)

Fig. 5 shows the fuel assembly maximum bow variations as a function of fluence for HIPER16™ design. Based on the results, it seems that the fuel assembly bow does not depend on the fluence.

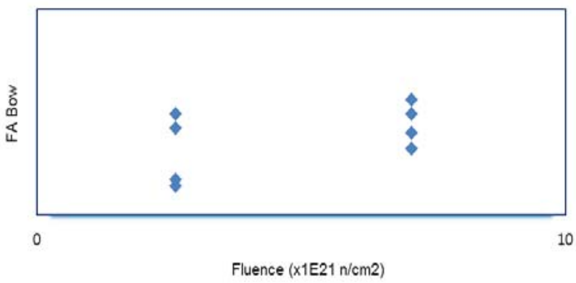


Fig. 5 Fuel Assembly Bow vs. Fluence

5. Conclusions

The fuel assembly bow characteristics of the HIPER16^{TM} fuel design have been investigated by analyzing the measured fuel assembly bow data after 1st and 2nd irradiation cycle of LTA.

(1) The typical shape of HIPER16^{TM} fuel assembly bow is “S” shape and the bow characteristics of HIPER16^{TM} fuel assembly design for ZIRLO^{TM} and HANA^{TM} material are very similar.

(2) The location of maximum fuel assembly bow of PLUS7^{TM} and HIPER16^{TM} fuel designs are different. However, the maximum fuel assembly bow values are almost same regardless of the location of maximum fuel assembly bow.

REFERENCES

[1] Sang-Youn Jeon et al., “Verification of HIPER16^{TM} Fuel Design for 16x16 CE-NSSS Type Nuclear Power Plants”, Transactions of the 19th Pacific Basin Nuclear Conference(PBNC 2014), Canada, 2014.

[2] Sang-Youn Jeon et al., “An Investigation on the Bow Characteristics of the PWR Fuel Assembly”, Transactions of the Korean Nuclear Society Autumn Meeting, Gyeongju, Korea, 2011.