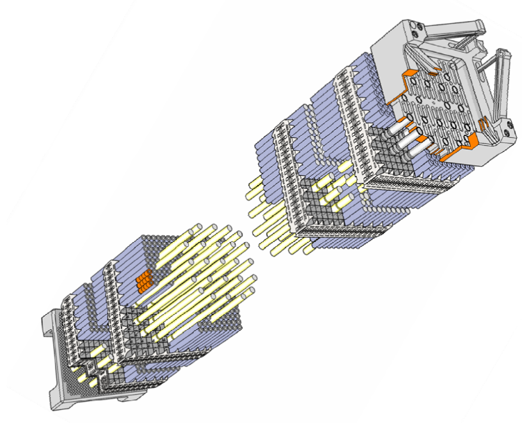
Development of Advanced PWR Fuel and Core for High Reliability and Performance



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MHI has developed pressurized water reactor (PWR) fuel assemblies and cores to increase the burnup mainly from the viewpoint of improving economic performance. Currently, fuel assemblies that can achieve the maximum fuel assembly discharge burnup of 55,000 MWd/t have been loaded in actual plants. Some fuel assemblies have already been irradiated as scheduled. MOX fuels were also fabricated under strict management in foreign countries and loaded to commercial power plants. As for uranium fuels, long cycle operating sequence and power up-rate, both of which are required for plant operation, can be addressed and it is possible to cope with further requests through only minor design changes. MHI will promote various development activities to not only develop more advanced PWR fuel assemblies /cores but also supply fuel assemblies to foreign countries.

1. Introduction

MHI has considerable operating experience with PWR fuel since it first supplied PWR fuel assemblies to Mihama Unit 1 of the Kansai Electric Power Co., Inc. in 1970.

To improve the plant economy, MHI started development programs to increase the licensed discharge burnup from 39,000 MWd/t to 48,000 MWd/t in the 1980s. In 2004, the licensed discharge burnup was raised from 48,000 MWd/t to 55,000 MWd/t with the fuel assemblies used in commercial reactors. During the period, MHI steadily implemented studies on improving the reliability, application of MOX fuels, and achievement of longer cycle plant operation based on the experience of previous fuel problems. In April 2009, MHI’s nuclear fuel operations (development, design, marketing, and sales) were integrated into Mitsubishi Nuclear Fuel Co., Ltd. (MNF) responsible for the fabrication of nuclear fuels. As a result, MNF became a company that could promote the nuclear fuel businesses comprehensively. Since then, MNF has been deploying its business activities together with MHI responsible for plant business operations.

Moreover, MNF is deploying fuel businesses for foreign plants along with the development of US-APWR/EU-APWR promoted by MHI.

Based on these backgrounds, the actual results of the fuel and core development and the future prospects are described below.

2. Experience and current status of fuel and core developments

2.1 Irradiation Experience in Japan

MHI has considerable fabrication and operating experience with PWR fuel assemblies since it first supplied two fuel assemblies for initial core to Mihama Unit 1 of the Kansai Electric Power

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Co. Inc. (KEPCO) in 1970. Since then, MHI has accumulated experience of fabricating nuclear fuels and produced about 18,600 fuel assemblies as of August 2009 (**Figure 1**).

Step 2 high burnup fuel assemblies (the maximum fuel assembly discharge burnup is 55,000 MWd/t) have been introduced to domestic PWR plants from 2004 and loaded to 14 of 24 plants in Japan as of August 2009. In KEPCO's Ohi Unit 4 to which Step 2 fuel assemblies were loaded first in Japan, the average fuel assembly discharge burnup reached about 53,000 MWd/t at maximum. MHI verified the validity of the behaviors of Step 2 fuel assemblies through the follow-up irradiation.

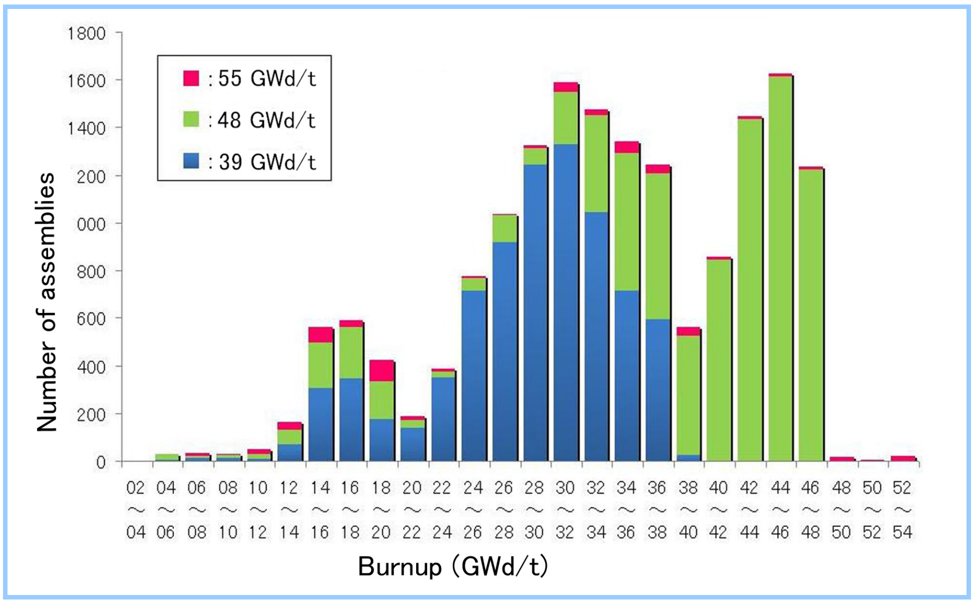


Figure 1 Burnup experience of Mitsubishi fuel assemblies (as of September 2009)

2.2 Overseas fabrication of MOX fuels and core design

MHI, as the total supplier of nuclear reactors and fuel assemblies, is introducing MOX fuels based on its extensive technical expertise in fuel design, core design, plant safety assessment, plant equipment effect assessment, transportation container design, MOX fuel fabrication, and acceptance of fuel assemblies at site according to the directions of the Japanese government and utilities.

As for MOX fuel assemblies, fuel specifications with a maximum discharge burnup of 45,000 MWd/t are adopted based on the Step 1 fuel design (the maximum fuel assembly discharge burnup is 48,000 MWd/t), of which there is considerable operating experience. MOX fuels were fabricated in the MELOX plant in France under strict quality assurance requirements and loaded to Genkai Unit 3 of the Kyushu Electric Power Co., Inc.

From the viewpoint of core design, the optimal plutonium concentration was determined taking into consideration the required operating period and the timing fuel loading, as well as licensing restrictions against MELOX plant and transportation containers before fabrication of MOX fuel assemblies. MHI not only strongly supported utilities in applying for imported fuel assembly inspection and in strict reviews by the Nuclear and Industrial Safety Agency (NISA) before acquisition of a construction permit relating to the introduction of MOX fuel assemblies but also carefully preparing the design environment, including establishment of verification processes that will be necessary to check the internal pressures of fuel rods and rationalization of the interface between core and fuel designs that will be necessary to design actual plant cores.

The MOX fuel core is designed to have sufficient safety margin compared to the conventional fuel core. As for the core management, MHI has executed various types of support, including modification of the core management codes necessary for MOX fuel safeguard, introduction of an advanced core monitoring system having accuracy comparable to the design codes, and integration of a MOX fuel core model into a plant operator training simulator.

In the future, MHI will completely monitor the behaviors of the MOX fuel core to assist the core management after the core starts operation.

2.3 Long cycle operation

When the extended-period operation (long cycle operation) is introduced, fuels will stay in the core for a longer period and the number of new fuel assemblies to be loaded will be increased and as a result the fuel design, core design, and safety assessment may be affected. For this reason, NISA is examining the verification methods used to evaluate the validity of the extended operating period of reactors based on the impact assessment on the extended operating period in typical plants.

For PWRs, NISA is examining the core design whose operating period is 15 months (the period from the start of power generation to shutdown is 16 months). Since the objective of this examination is to seek methods to verify the validity of the extended operating period without application of construction permit change and it is essential make a detailed comparison of the core characteristics observed in the prolonged operating period to those observed in the current operating period, MHI is executing analyses equivalent to or more precise than those used for the construction permit application to support the utilities.

Since the operating period is not substantially extended in these typical plants compared to the current period, the features representing the long cycle operation were not clearly observed and the core characteristics were almost the same as those measured in the normal operating period and, therefore, impacts on the fuel design, core design, and safety assessment were minor.

After the examination on the typical plants is completed, utilities will apply the security change permits relating to the extended-period operation on a plant-by-plant basis one after another. After that, we will propose those fuels improved to reduce environmental loads and achieve higher economic performance and operating methods for the new core taking into consideration further operating period extension although the concrete scheme depends on the plant operation plan of each utility.

2.4 Development of fuels and cores for US- and EU-APWRs

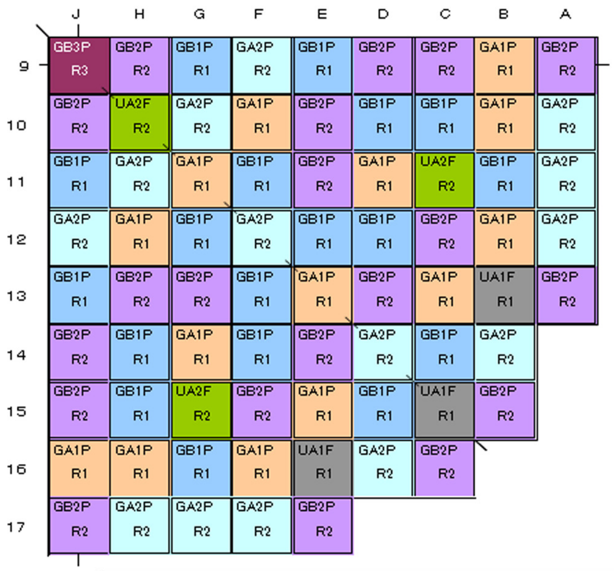
US- and EU-APWRs are based on domestic APWRs and, therefore. MHI has been developing fuel assemblies for these new plants. The major difference between US/EU-APWRs and domestic APWRs from the viewpoint of fuel and core designs is the effective fuel length: i.e., the fuel stack length is extended from 12 ft to 14 ft. The extended effective fuel length permits reduction of the linear power density, contributing to increased margins for both core safety and fuel integrity.

Fuel assemblies for US- and EU-APWRs are designed based on Mitsubishi 17×17 Type Step 2 high burnup fuel assemblies with which MHI has considerable operating experience in Japan. To cope with the extension of fuel length, the number of grids is increased to 11. As a result, the grid-to-grid span of the new fuel is equivalent to or shorter than the conventional 12-ft fuel (characterized by 9-grids design) to reduce the flow induced vibration and maintain the resistance against the wear by the flow induced vibration between the fuel rod and grid.

A short span also improves the thermal-hydraulic characteristics. In response to the extended fuel rod, a plenum is added to the bottom section of the fuel rod to decrease the internal pressure of the fuel rod. The components of the fuel assembly are basically the same as those used in the Mitsubishi 17×17 Type Step 2 high burnup fuel. The Mitsubishi Type I grid, which features superior fuel rod holding capability, is used. The mid-grids are made of Zircaloy, which reduces the radiation exposure and effectively utilizes neutrons, while upper and lower grids are made of Inconel to firmly hold the fuel rods and thus mitigate the flow induced vibration. Improved design is applied to top and bottom nozzles. For the top nozzle, the profile and arrangement of flow holes are changed to improve the flow to the upper section of the core. An impurity filtration feature is added to the bottom nozzle to effectively capture foreign materials and enhance the performance and reliability compared to the conventional design.

While specifications of US- and EU-APWRs such as core thermal output, number of fuel assemblies loaded to the core, and neutron reflector are the same as those for domestic APWRs, the core is designed to achieve 24-month operation taking into consideration the experience of long cycle operation in foreign countries. Concretely speaking, the effective fuel length is extended to 14 ft as described above to reduce the linear power density. This design arrangement improves the plant economy thanks to the increased availability factor while controlling excessive increase of new fuel assemblies needed for the 24-month operation scheme. Since the prolonged plant operation dramatically changes the axial power distribution during the operation, MHI employs those fuels in which gadolinia added fuels are partially placed along the fuel rod to increase the heterogeneousness and mitigate the change in power distribution.

As for the fuel loading pattern, MHI employs a core design that incorporates the requirements from foreign customers: i.e., L3P (low leakage loading pattern) is selected where irradiated fuels are arranged at the outer periphery of the core as shown in **Figure 2**. The design control document that describes these standard design features is under review by NRC, a U.S. government's regulatory body, toward earlier licensing.



1	GB3P	1	Region N-2 4.55wt%, 10wt%Gd×24【part length】 *
2	UA2F	12	Region N-1 4.55wt%
3	GA2P	52	Region N-1 4.55wt%, 6wt%Gd×16【part length】 *
4	GB2P	64	Region N-1 4.55wt%, 10wt%Gd×24【part length】 *
5	UA1F	12	Region N 4.55wt%
6	GA1P	52	Region N 4.55wt%, 6wt%Gd×16【part length】 *
7	GB1P	64	Region N 4.55wt%, 10wt%Gd×24【part length】 *

*【part length】: 15cm of a top and bottom of Gd fuel rod edge is replaced from the Gd pellet by the UO2 pellet.

Figure 2 Fuel loading pattern for 24-month operation (example)

3. Future Activities for Improved Fuel and Core

3.1 Fuel design improvement

MNF is developing new fuel cladding materials to meet the requirements of further burnup extension of PWR fuels and a high duty operation in the future.

Mitsubishi Developed Alloy (MDA) is a new material developed based on the concept of improvement of corrosion resistance. This new material has the basic characteristics of the Zircaloy-4 fuel claddings (more than 3 million Zircaloy-4 claddings were irradiated in reactor cores). More than 100,000 MDA fuel claddings for 55,000 MWd/t fuels have already been irradiated in cores. To cope with the requirements of further burnup extension and a high duty operation, it is necessary to furthermore improve the corrosion resistance of the cladding and, therefore, the development of M-MDA™ (Modified MDA) is underway toward the goal: i.e., achieving further improvement of cladding corrosion resistance while maintaining the basic characteristics of MDA. Fuel claddings made of M-MDA™ have been irradiated in a commercial PWR reactor in Spain and the fourth cycle of an irradiation test has been completed. It has been verified that the M-MDA™ has excellent corrosion resistance even in the range of fuel rod burnup of more than 70,000 MWd/t compared to MDA (**Figure 3**). When this irradiation phase is completed, we will implement post-irradiation tests for M-MDA™ toward the practical application of the new material in the future.

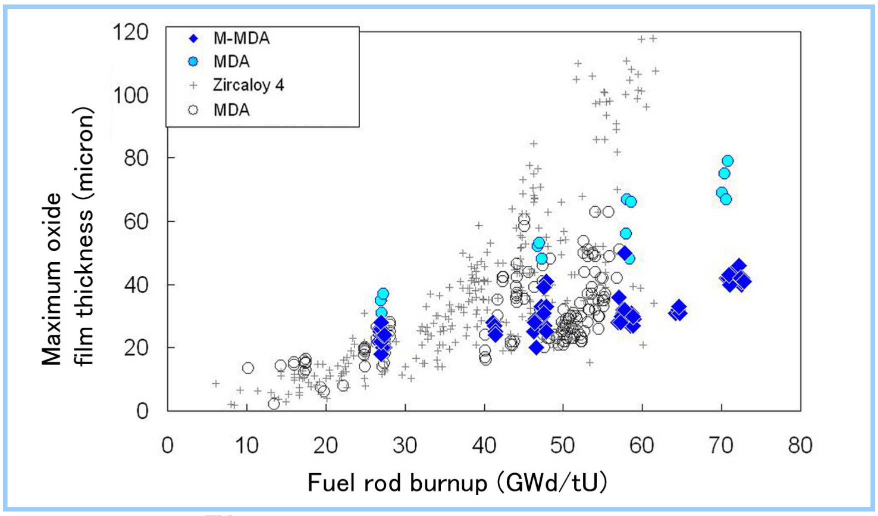


Figure 3 M-MDA™ corrosion data in reactor

To meet the future fuel performance requirement under a higher duty operation, the development of J-Alloy™, which contains more Nb than the Zr-Nb alloy whose higher corrosion resistance has already been confirmed, is being conducted jointly with domestic industrial partners.

In Japan, fabrication and out-of-pile tests were executed for J-Alloy™ claddings to examine the mass-productivity, increased corrosion resistance, and low oxygen absorbability. In Spain, the second cycle of the irradiation is underway in a commercial PWR reactor. We will continue these irradiation tests until the fuel burnup reaches 70,000 MWd/t. Some of the fuels irradiated in the first cycle will be transported to the post-irradiation test facility and be examined for the future practical application of the new cladding material.

We are planning to introduce fuel claddings made of M-MDA™ and J-Alloy™ according to the load environment and specification requirements for fuels.

3.2 Advanced core design

MHI is promoting improvement of core design and related technologies to appropriately and flexibly address the future needs brought to domestic and foreign PWR plants, including further burnup extension and power increase.

In Japan, MHI is steadily improving the core design technologies through the reload core design for all PWRs to cope with the current requirements of further burnup extension and long cycle operation. As Step 3 of the burnup extension program, we are studying how to achieve high licensed discharge burnup whose maximum fuel assembly discharge burnup is equivalent to 55,000 MWd/t defined in Step 2 under the precondition that the uranium enrichment will not exceed 5 wt%, from the viewpoint of fuel operation.

As for the recent foreign business development, we started the studying of advances in core design to fit the domestic core design for the different foreign fuel operation. In foreign plants, there is such tendency that L3P is positively applied to increase the neutron utilization efficiency and thus lower the uranium enrichment to the extent possible. Therefore, many plants employ an operation scheme such that different uranium enrichment and gadolinia concentration are selected per reload core from the standpoint of optimization of the core in order to control the core reactivity and power peaking. Although this operation scheme makes the core design more complicated and requires a speedy design process, we will promote developments to meet these needs in an appropriate manner.

MHI has started development of the core deign code called the GALAXY/COSMO-S system to improve the core design tool at the same timing as the application for the US-APWR design certification. MHI is planning to use this code system into which MHI's experience of the PWR core design are integrated for the purpose of optimization of the core design system as the kernel of the core design tool so that the new code system will replace the PHOENIX-P/ANC system used in the core design of domestic PWR plants and the PARAGON/ANC system used in the core deign of US-APWR. This new-generation code takes in the latest nuclear data and neutron flux calculation methodology to offer a high-speed and high-accuracy three-dimensional analytical approach to permit execution of sophisticated safety analyses through the integration of nuclear, thermal, and kinetic calculation functions.

The near-future objective of the core management technologies is to positively utilize the core management system to more appropriately conduct core parameter monitoring and abnormal event diagnosis, both of which are necessary to meet the security requirements. In the long-term plan, MHI would like to promote R&D activities to maximize plants' operational advantages by studying the application methods for continuous and direct monitoring based on the introduction of FID (fixed in-core detector).

3.3 Development of new-generation LWR fuel and core

MHI is participating in the new-generation LWR development project, a national project. The new-generation LWRs aim at increased economical performance and deceased environmental load through considerable reduction of generation costs. To reach this goal, it is necessary to improve the availability factor, decrease the fuel cycle costs, and decrease the number of reload fuels. MHI is developing innovative PWR fuels (cladding materials) that will be used for the new-generation LWRs and will endure the ultra high burnup that substantially exceeds the current level (i.e., the licensed discharge burnup will be more than 80,000 MWd/t).

4. Conclusion

MHI has developed fuel assemblies and cores through R&D activities on fuel burnup extension and advanced core design. In the future, MHI, together with MNF, which has taken over the nuclear fuel business from MHI, will develop more advanced fuels that permit diversified fuel operation opportunities brought by higher burnup fuels, long cycle operation, and other schemes with the objective of increased reliability and economic efficiency of nuclear power plants, and will deploy the nuclear fuel business for foreign plants.