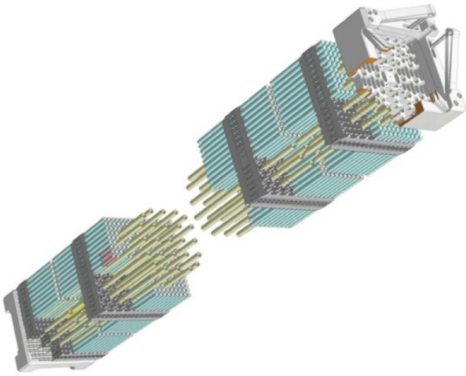
Development of M-ReX™ for High Reliability and High Seismic Performance

- Study for Development of Accident Tolerance Fuel Cladding -



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As part of efforts toward improved safety and reliability for light-water reactors, Mitsubishi Heavy Industries, Ltd. (MHI) and Mitsubishi Nuclear Fuel Co., Ltd. (MNF) have been working on the advancement of reactor fuel. In the short and medium term, we are undertaking the development of the MNF Robust and eXcellent performance fuel assembly (M-ReX™) with the purpose to increase the seismic resistance and reliability of the fuel, aiming to achieve stable and on schedule operation of light-water reactors. In the medium and long term, we plan to develop a Chrome (Cr)-plated Zirconium (Zr)-base alloy fuel cladding that will have higher accident tolerance than the existing Zr-base alloy, as well as a Silicon Carbide (SiC) fuel cladding that is expected to achieve an even higher level of accident tolerance. This report provides an overview of our progress relating to these new types of fuel cladding.

1. Introduction

The development of M-ReX™ is underway with the target of its implementation in nuclear power plants in the 2020s in order to improve their seismic resistance and reliability. MHI is also working on the development of accident-tolerant fuel cladding so that it could be implemented in practical use as early as in the 2030s. This report introduces the related development concepts and progress.

Figure 1 gives an overview of a fuel assembly for a Pressurized Water Reactor (PWR). The top and bottom nozzles and spacer grids are connected to the control-rod guide thimble (hereinafter called the guide thimble) and the fuel rod is held by the spacer grids. The fuel assembly is supported in the reactor vessel via the top and bottom nozzles. The top and bottom nozzles, guide thimbles and spacer grids form together the framework to support the fuel rods.

2. Development of M-ReX™

2.1 Concept

Improved seismic resistance (increased structural strength)

In light of the lessons learned from the Fukushima Daiichi Accident caused by the Great East Japan Earthquake, improved safety and design taking into account natural phenomena have been particularly required for light-water reactors. In terms of the fuel assembly in particular, it must be designed to have a sufficient level of tolerance to earthquakes, as necessary in the design of nuclear power plants. However, in order to secure an extra margin to increase safety, it is necessary to improve the seismic resistance by changing the materials and structure, or to refine the assessment procedure. M-ReX™ aims to improve the hardware performance thanks to materials and structure optimization. The features allowing to achieve such better performance are described as follows.

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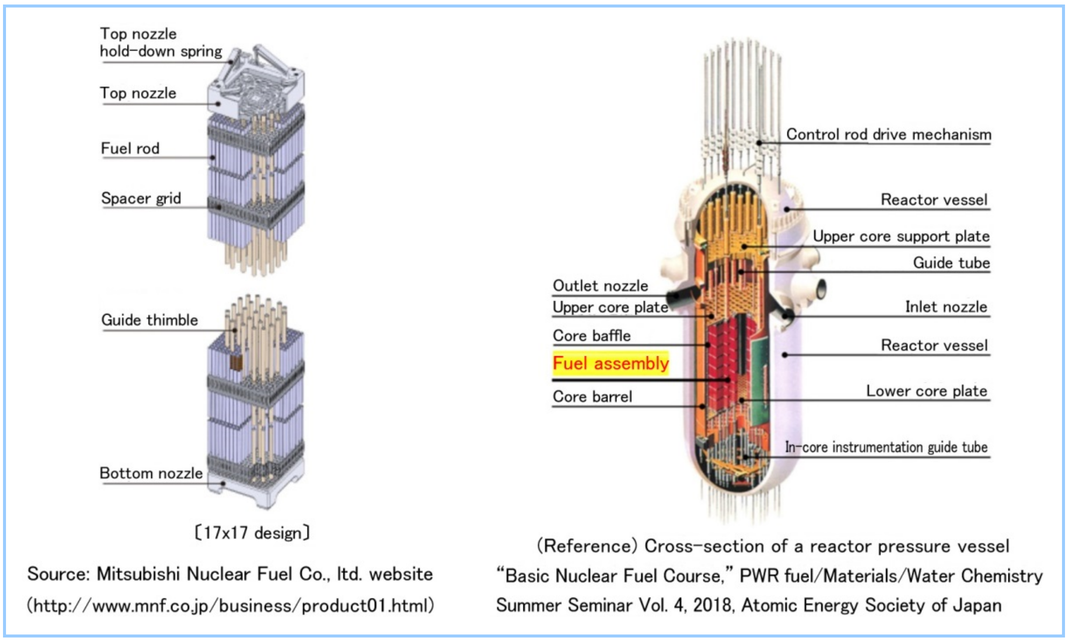

Figure 1 Overview of fuel assembly for PWR

(1) Application of high-strength materials to structural members

The seismic resistance is increased through the application of Modified-Mitsubishi Developed Alloy (M-MDA^{TM}), which has a higher strength than Zircaloy-4, the conventionally-used material, to the structural members such as the guide thimble and spacer grid (see 2.2).

(2) Adjustment to structure of spacer grid and guide thimble

Adjustments to the design of the spacer grid and a partial increase in the thickness of the guide thimble improve the structural strength of the fuel and thereby increase the seismic resistance (see 2.3).

Improved reliability

As a measure against the fuel leaks that occurred from 2008 to 2010, the first design of Zero-Defect Performance (ZDP-1), reliability-improved fuel, has been developed and implemented in nuclear power plants(1). Meanwhile, while following ZDP-1's design concept, the reliability of M-ReX^{TM} has also been improved through the introduction of fundamental measures against the presumed leak factors, in order to further contribute to reducing the risks associated with the unplanned shut-down of nuclear power plants due to fuel leaks. Furthermore, in an attempt to contribute to expanding the plant safety margin, there has also been a significant effort made to increase the reliability of the materials, the features of which are as follows.

(3) Improved fuel rod supporting performance

The reliability is increased by changing the spring shape of the spacer grid holding the fuel rod and improving the fretting wear resistance at the rod-supporting portion (see 2.4).

(4) Application of materials with improved corrosion resistance to fuel cladding

As described below, we use materials with better corrosion resistance in M-ReX^{TM}. The increased corrosion resistance during normal operation reduces the amount of hydrogen absorbed in the Zr-base alloy cladding. As a result, the material deterioration caused by hydrogen is reduced, which means that an extra margin is created in terms of the safety assessment (see 2.2).

An overview will be provided in the following sections.

2.2 Application of M-MDA^{TM} material

Development background

(1) Improved corrosion resistance

M-MDA^{TM} was initially developed for use in fuel cladding and, as shown in **Table 1**, its composition is based on the Mitsubishi Developed Alloy (MDA) that has been already applied to nuclear power plants as a highly corrosion-resistant material for fuel cladding. The amount of Sn, which is an additive element, is reduced for further enhancement of corrosion resistance, while increasing the amount of Cr/Fe to achieve a reduced hydrogen pickup fraction [(2)(3)].

Table 1 M-MDA material composition

Material	Sn	Nb	Fe	Cr	Zr
M-MDA	0.5	0.5	0.3	0.4	Bal.
(Reference) MDA	0.8	0.5	0.2	0.1	Bal.
(Reference) Zircaloy-4	1.5	—	0.2	0.1	Bal.

(2) Enhanced mechanical strength

The increase in the joint amount of Fe and Cr enhances the mechanical strength to the extent that it is more than sufficient to cancel out the decrease thereof due to the reduction of the Sn amount.

The M-MDA™ cladding has been irradiated at actual overseas nuclear power plants in joint research projects with electric power companies. The post-irradiation tests have confirmed the superiority of M-MDA™ compared to the conventional materials in terms of corrosion resistance (**Figure 2**) and mechanical strength (**Figures 3** and **4**) [(3)].

Application to guide thimble and spacer grid

As shown in Figures 3 and 4, it has been confirmed that M-MDA™ tends to have a higher mechanical strength than Zircaloy-4, the conventional structural material. The application of M-MDA™, which has a higher strength than the conventional material, to structural members such as the guide thimble and spacer grid, helps to increase the seismic resistance.

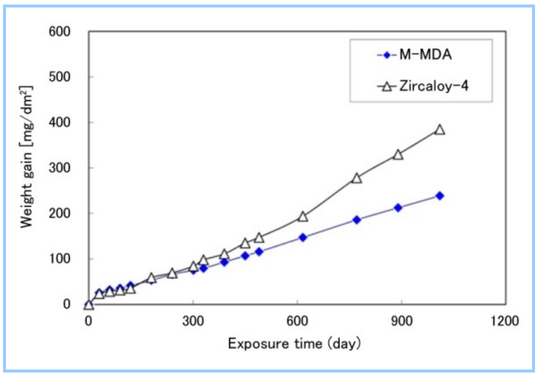

Figure 2 Corrosion behavior of guide thimble

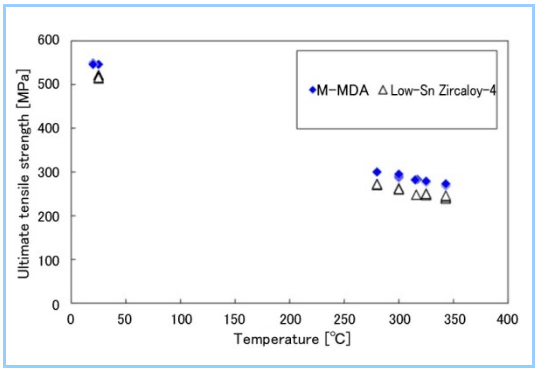

Figure 3 Ultimate tensile strength of guide thimble

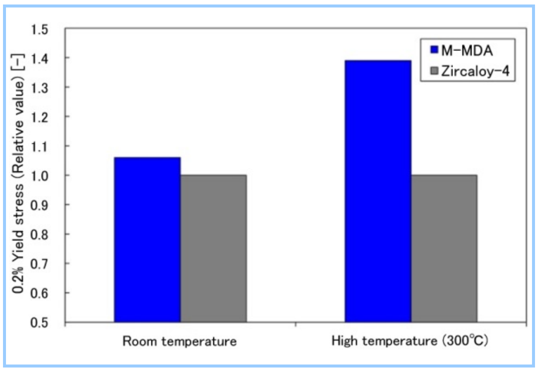

Figure 4 Yield stress of sheet for spacer grid

2.3 Enhancement of structural strength by design alterations

(1) Increased seismic resistance of spacer grid

The spacer grid is, as shown in Figure 1, a structural member that holds the fuel rod. When vibrations occurs during an earthquake, the structural components in the core or the adjacent fuel assemblies collide with the spacer grid, which creates an impact load on the spacer grid. Accordingly, in M-ReX™, we focused on the elastic limit load as an index of the seismic performance of the spacer grid and worked on its improvement. Specifically, we applied M-MDA™, which has a higher strength than the conventional Zircaloy-4, to the spacer grid material (see Figure 4). At the same time, we increased the height (dimension) of the spacer grid (**Figure 5**) to the extent that it would not affect the coolant flow. In this way, we have confirmed in spacer grid impact tests that the spacer grid elastic limit load, which is an index of the seismic performance of the spacer grid, is improved by approximately 30% compared with one made of the conventional material.

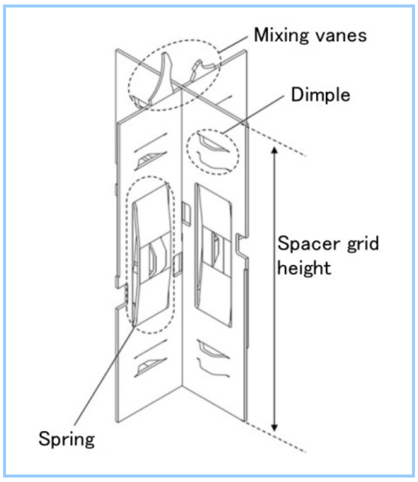

Figure 5 Spacer grid outline

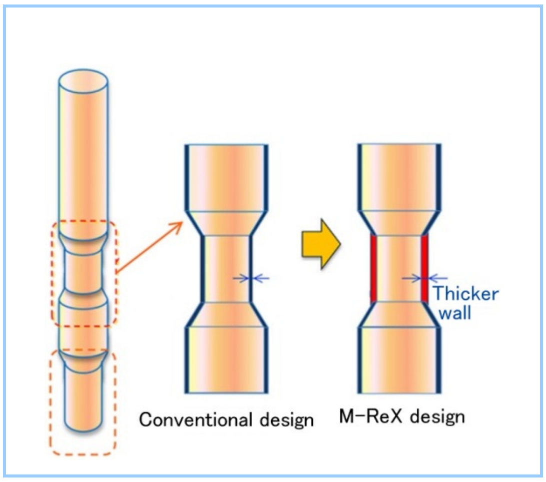

Figure 6 Measures for increasing margin in seismic resistance of guide thimble

(2) Increased seismic resistance of guide thimble

The guide thimble is a structural member that constitutes a part of the supporting framework as shown in Figure 1, which also serves as a path for the control rod to be inserted through the fuel assembly. Therefore, in M-ReX™, the strength is enhanced through the application of M-MDA™ to the guide thimble just like the spacer grid. We have confirmed that this improves the strength of the guide thimble by approximately 30% (see Figure 3).

Furthermore, at the bottom of the guide thimble, there is a portion where the inner diameter is reduced (hereinafter called the small diameter portion) in order to significantly decelerate the free fall of the control rod during a reactor trip by utilizing the coolant resistance effect. When vibration amplitude increases in an earthquake, the compressive load on the guide thimble increases at the bottom of the fuel assembly in particular. Accordingly, in M-ReX™, in addition to applying M-MDA™, we enhanced the strength by increasing the thickness of the wall of the small diameter portion of the guide thimble, but only to the extent that it would not affect the pressure drop characteristics (**Figure 6**). We have confirmed that, in this way, the guide thimble strength increases further by about 5%, or about 35% when combined with the M-MDA™ application.

2.4 Increased fretting wear resistance

In the ZDP-1 reliability-improved fuel design, which has already been implemented in nuclear power plants, some measures have been taken for enhancing fretting wear resistance as shown in **Figure 7** (homogeneously porous bottom nozzle with a debris filter and long bottom-end plug). As a fundamental measure against fuel leak events and in addition to the above concept, M-ReX™ has a further enhance fretting wear resistance thanks to the improved design of the grid springs and dimples (Figure 5) that directly hold the fuel rod.

(1) Improved fuel rod supporting performance

During use inside the reactor, the outer diameter of the fuel rod decreases due to the impact of the coolant pressure. Therefore, it is necessary to design the springs so that the fuel rod is held properly for the entire duration of service. Meanwhile, as a results of the neutron irradiation defects accumulating in the axial direction of the fuel rod, the rod tends to extends axially during its use in the reactor. Therefore, an excessive level of fuel rod supporting performance would cause adverse effects by preventing the fuel rod from extending and thus causing bending of the fuel rod. Accordingly, we have adopted a spring design that secures a similar level of initial fuel rod supporting performance as the conventional design, while increasing the extent of the supporting deflection by reducing the spring rigidity. Consequently, the design would be able to maintain the fuel rod supporting capability by letting the springs conform to the reduction in the outer diameter of the fuel rod even if the fretting wear progressed in the fuel cladding.

(2) Increased contact area in fuel rod supporting portion (fretting wear reduction)

Our design reduces the fretting wear depth by approximately 20% by increasing the contact area with the fuel rod.

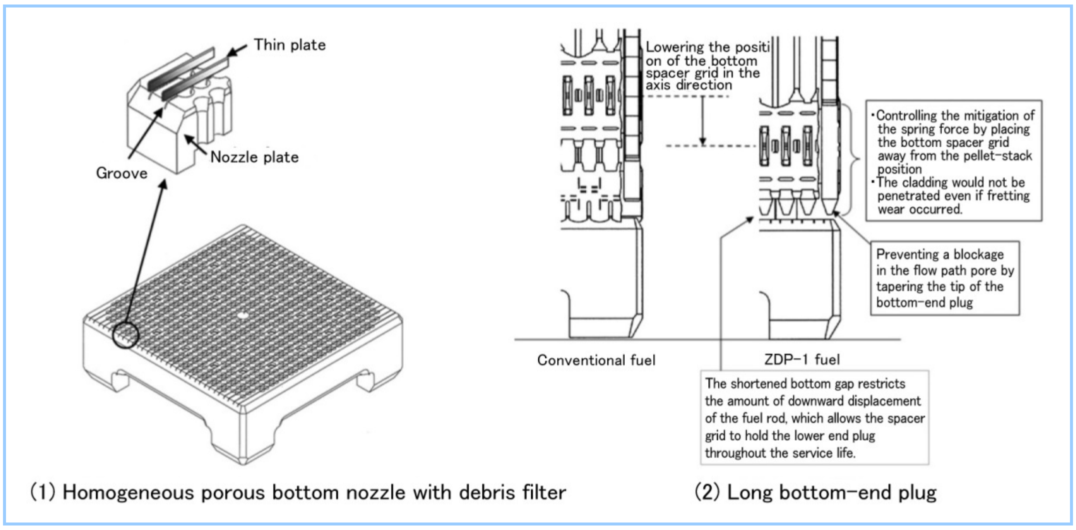

Figure 7 Measure for enhancing fretting wear resistance

2.5 Acquisition status of verification data

In order to confirm the applicability to nuclear power plants and the possible coexistence with conventional fuels, we have conducted various verification tests.

(1) Mechanical tests on fuel assembly

From the results of vibration tests and rigidity tests on the fuel assembly, we have confirmed that the M-ReX™ has mechanical properties equivalent to existing fuels. Therefore, it is expected to achieve positive effects in terms of the improvement in the seismic resistance described in the previous sections when the same seismic assessments of ground motions are conducted with M-ReX™ as we would with conventional fuels.

(2) Pressure drop measurement

From the results of pressure drop tests, we have confirmed that M-ReX™ can coexist with conventional fuels since it has a similar level of pressure drop in the fuel assembly and spacer grid as the conventional ones.

2.6 Further development and prospects

We will continue the verification tests and assessments of the detailed design so that we can propose the implementation of M-ReX™ to our customers. We are also working on the development of a new spacer grid that is designed to have larger mixing vanes in order to enhance the flexibility of core operation with an increased thermal margin, with its projected implementation in nuclear power plants in the 2020s (**Figure 8**).

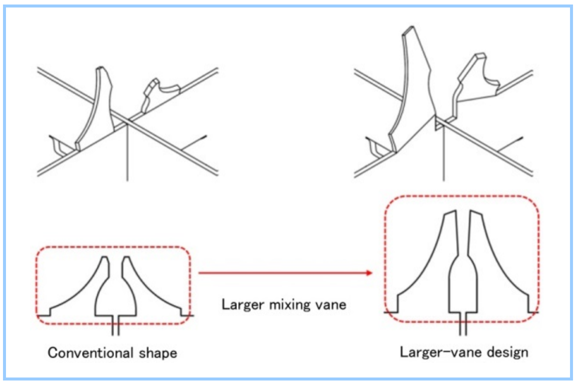

Figure 8 Comparison between 2 different mixing vane shapes of spacer grid

3. Development of accident-tolerant fuel cladding

3.1 Concept

In the aftermath of the Fukushima Daiichi Accident caused by the Great East Japan Earthquake, accident-tolerant fuel has attracted attention around the world as a new technology that has the potential of controlling progression to serious situations such as core damage or hydrogen explosion.

Enhanced oxidation resistance (suppressing progress to severe accidents)

If water supply to the reactor core is cut off at the time of an accident, the fuel cladding is eventually exposed and becomes extremely hot where the cladding and water vapor cause an oxidation reaction. The heat from the oxidation reaction increases the cladding temperature dramatically where hydrogen generation becomes prominent, while the embrittlement of the cladding advances. Accordingly, a new material that would increase the oxidation resistance in a high-temperature steam environment is very promising for use in accident-tolerant fuel cladding.

Increased cooling performance (Measure against FFRD)

Attention is currently focused on a phenomenon called Fuel Fragmentation, Relocation and Dispersal (FFRD), which occurs at the time of a Loss of Coolant Accident (LOCA), where fuel pellets break up into fine pieces inside a fuel rod that has reached an extremely high degree of burnup, and the pieces are released out of the fuel rod through ruptures in the cladding. Therefore, it is also necessary to take measures against FFRD incidents including high-degree burnup from a hardware aspect in the advancement of fuel for light-water reactors.

Accident-tolerant fuel cladding is designed to increase these required performances, and its features for achieving them are as follows.

(1) Application of Cr-coated Zr-base alloy fuel cladding (Cr-coated cladding)

We aim to enhance the oxidation resistance and cooling performance at the time of an accident by applying the Cr-coated cladding, the technology of which is based on the Zr-base alloy that has a wide range of practical applications in fuel cladding (see 3.2).

(2) Application of SiC Cladding

We aim to further enhance the oxidation resistance and cooling performance at the time of an accident through the utilization of a SiC-combined material, which is highly heat-resistant and hardly reactive to water vapor, in fuel cladding (see 3.3).

Both materials can contribute to advanced reactor core operation including longer operation periods, while increasing the level of safety. The related development progress is provided in the following sections.

3.2 Progress in development of Cr-coated cladding

We have already confirmed the manufacturing feasibility and the basic performance in terms of enhanced LOCA resistance properties of the Cr-coated cladding[(4)].

(1) Current status

With respect to the Cr-coated cladding, which is technically based on a Zr-base alloy that has a wide range of applications in fuel cladding, with a goal to achieve practical use in existing PWRs sometime around 2030, we are currently working on prototypes and experiments while taking into consideration the development of accident-tolerant fuels currently underway both in Japan and overseas.

(2) Accident-tolerance effect

Using a prototype cladding sample, we conducted a test to confirm the fuel integrity standard under LOCA conditions (PCT1200°C/15%ECR) by simulating a retention period with oxidation twice as much as the standard extent (30%ECR) in the conventional Zr-base alloy cladding. From the results of the simulation test, while the conventional Zr-base alloy cladding broke due to the heat shock caused by rapid water cooling, we confirmed that the Cr-coated cladding did not break (**Figure 9**). We believe that this is because the strength of the base material was maintained as the oxidation in the Zr-base material was prevented thanks to the Cr coating. As we can see from the results, the formation of the Cr coating is expected to enhance the oxidation resistance of the fuel cladding. Furthermore, we have obtained a positive result from a similar LOCA simulation test where the Cr coating was able to limit the formation of ballooning in the cladding at the time of the LOCA event. This means that the long-term cooling performance after a LOCA event can be expected to improve since the flow path of the coolant is less likely to be blocked.

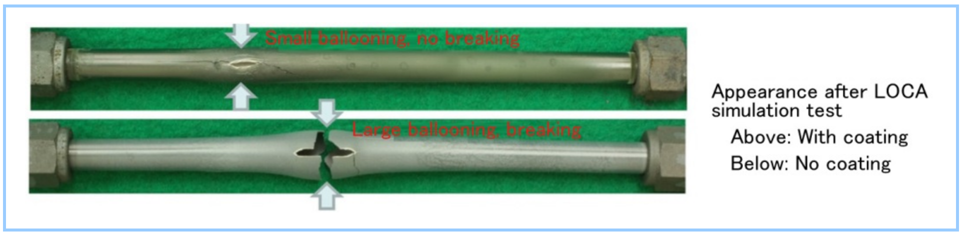

Figure 9 Confirmed accident-tolerance effect

(3) Normal operation performance

The prototype Cr-coated cladding has a uniform thickness and the Cr coating formed on its outer surface shows no peeling or cracks even after tensile deformation. On the outer surface where the coating is formed, there is an increase in the corrosion resistance and hardness. As described so far, it is expected that the Cr coating will enhance performance during normal operation in various aspects including corrosion resistance and fretting wear resistance.

(4) Further development toward practical applications

Targeting its application to nuclear power plants, we will continue working on the Cr-coated cladding material property testing, on the irradiation tests for better understanding of irradiation behaviors and on the development of analytical models and codes for evaluating the impact of the application of the Cr-coated cladding on the safety design.

3.3 Progress in development of SiC cladding

We have positive prospects for the successful application of the SiC cladding technology based on our collected basic data and our conducted analyses so far.

(1) Current status

The SiC-combined material is a very promising candidate material for accident-tolerant fuel cladding as described above. On the other hand, compared with the Cr-coated cladding, there are some issues to overcome before applying the SiC-combined material to nuclear power plants as explained below. For example, an extensive collection of material property data would be necessary for the fuel design.

(2) Accident-tolerance effect

We have confirmed, according to the accident simulation analysis, that the SiC cladding can suppress hydrogen generation and secure a longer time before core meltdown even at the time of a severe accident. Furthermore, LOCA simulation tests have confirmed that there are no ballooning, ruptures or oxidation in the SiC cladding even under a LOCA situation, and that it maintains its shape without breaking after being exposed to a heat shock caused by rapid water cooling, which proves that it has a sufficient level of tolerance to the LOCA phenomena.

(3) Normal operation performance

Since the SiC cladding has a low level of thermal conductivity and mechanical strength in terms of its irradiation materials, if the same design as existing fuels was applied, it would end up breaking due to the stress caused by contact with thermally expanded fuel pellets inside cladding. Accordingly, we think it is possible to find a successful design with some improvements such as lowering the fuel pellet temperature and controlling contact between fuel pellets and cladding. However, in order to establish a fuel design that is applicable to nuclear power plants, it is necessary to make some improvements to the material properties, i.e., an increase in the thermal conductivity and mechanical strength, supported by the advancement of manufacturing technologies, as well as to have an extensive collection of material property data including irradiation behaviors.

(4) Issues in practical application

Besides the challenges in a successful fuel design as described above, there are some other issues in the practical use of the SiC cladding, such as the elution of Silicon to coolant and damage in transportation. These issues would not immediately deny the successful application of the SiC cladding, but they definitely need to be dealt with before it is introduced for practical use in the future, so it is necessary to develop some technology options in terms of improvement in water quality control and transportation casks.

3.4 Further development and prospects

With respect to accident-tolerant fuel cladding, we will continue working on the development of the Cr-coated cladding, targeting its application to nuclear power plants sometime in the 2030s.

4. Conclusion

As part of our efforts toward increased safety and reliability of light-water reactors, MHI is working on increasing the sophistication of reactor fuels through the development of M-ReX^{TM} fuel design as well as accident-tolerant fuel cladding.

In terms of M-ReX^{TM}, we have been able to enhance the seismic resistance by utilizing the M-MDA^{TM} material and adjusting the designs of structural members. On top of the ZDP-1 design concept, the reliability has been further enhanced by updating the design of the fuel rod supporting portion in the spacer grid. We will continue working on our verification tests and detailed design assessments so that we can propose the introduction of M-ReX^{TM} to our customers.

With respect to accident-tolerant fuel cladding, by utilizing Cr-coated Zr-base alloy fuel cladding, which is technically based on a Zr-base alloy with a wide range of practical applications in fuel cladding, we aim to enhance the corrosion resistance and fretting wear resistance as required in individual usage environments, while attempting to control progression to severe accidents at the time of a LOCA event and improve the cooling performance at the same time. We will continue working on development in the irradiation test, analytical model and coding toward practical applications.

MHI and MNF are committed to fuel advancement and plan to take advantage of the various benefits described in this report, such as the increased seismic resistance of light-water reactors, an extended safety margin and the application of advanced core operation in the future.

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