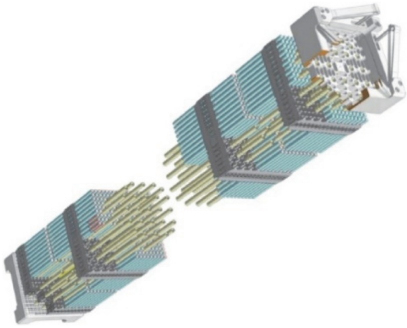
Development of Advanced Fuel for Improvement of PWR Safety and Operation - Development of Accident Tolerance Fuel Cladding -



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Mitsubishi Heavy Industries, Ltd. has been developing accident-tolerant fuel cladding tubes with improved performance under normal operation and in the event of an accident as part of its efforts to improve the safety of light water reactor plants and advancing core operation. In addition, aiming at implementation to actual plants in 2030s, data necessary for fuel rod design are being obtained by various performance verification tests and fuel rod irradiation tests in a research reactor in the United States.

1. Introduction

Figure 1 shows an overview of a fuel assembly for a Pressurized Water Reactor (PWR) made by Mitsubishi Heavy Industries, Ltd. (hereinafter referred to as MHI). The fuel assembly has a top nozzle, a bottom nozzle, and spacer grids connected to a guide thimble, and approximately 300 fuel rods are bundled by the spacer grids. The fuel cladding tube, which encapsulates the fuel pellets inside a fuel rod, is a critical component for the safety of the core and the integrity of the fuel during normal operation.

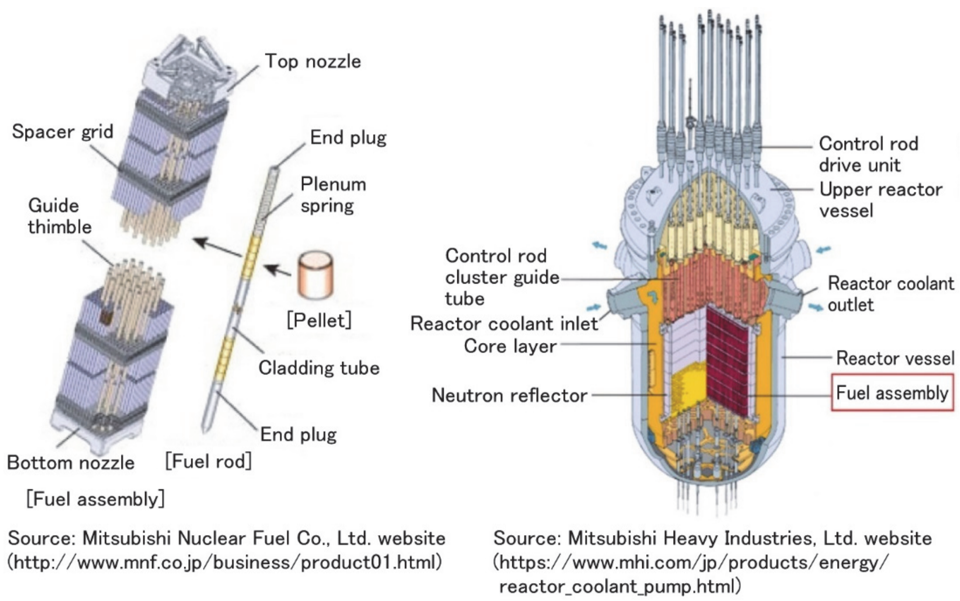

Figure 1 Overview of fuel assembly for PWR

Following the Fukushima Daiichi Accident, accident-tolerant fuel (hereinafter referred to as ATF) has attracted worldwide attention and is being developed as a technology to suppress the progression to severe accidents such as core damage and hydrogen explosions [(1)]. MHI has been developed ATF aimed at improving the accident tolerance of fuel cladding tubes. This report presents an overview and status of our development of ATF.

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2. Overview of development of ATF cladding tubes

ATF cladding tubes can contribute to enhance the safety of PWR by improving the high temperature oxidation resistance in the accident including severe accident. MHI has been developing the Chromium (hereinafter referred to as Cr)-coated fuel cladding tube whose substrate is zirconium (hereinafter referred to as Zr)-based alloy fuel cladding tube proven as the fuel cladding tube for commercial PWR. Since the Cr is superior oxidation resistance than Zr-based alloy in normal operation, Cr-coated fuel cladding tube can also contribute to advancing core operation such as burnup extension and power uprate.

With the aim of achieving its implementation in commercial PWRs in the 2030s, MHI is participating in the Ministry of Economy, Trade and Industry's project to develop technologies to improve the safety of nuclear power plants, and is promoting (i) fundamental technology development and (ii) implementation study of the ATF cladding tube. Currently, we are in the final stage of (i) fundamental technology development, to verify the improvement of oxidation resistance and the effect of Cr coating on the physical properties and behavior of fuel cladding tubes. At the same time, we are conducting irradiation tests at the Advanced Test Reactor (hereinafter referred to as ATR) in the United States under the Japan-US cooperative framework to confirm the effects of irradiation for the step up to the phase of (ii) implementation study. Our plan in the phase of (ii) is to confirm the applicability of the system to commercial PWRs through irradiation of a small number of fuel rods using Cr-coated fuel cladding tubes in a Japanese commercial PWR, followed by implementation.

Next, the following paragraphs show two advantages of introducing Cr-coated fuel cladding.

(1) Improvement of safety in the event of an accident (improvement of oxidation resistance at high temperatures, suppression of fuel cladding tube rupture in the event of a loss-of-coolant accident (hereinafter referred to as LOCA)).

When fuel cladding tubes becomes high-temperature due to degraded core cooling conditions caused by a loss of coolant in the reactor, fuel cladding tubes undergoes an oxidation reaction with steam, resulting in embrittlement. In the event of a LOCA, in which a large amount of primary coolant is lost due to pipe rupture or other causes, some of fuel cladding tubes burst due to decrease in its mechanical strength caused by a temperature rise in addition to an increase in the pressure difference between the inside and outside of the fuel rods. The oxidation reaction occurs at the inner surface of the fuel cladding tubes by steam flow into the inside of them through burst opening, resulting in further accelerating embrittlement of the fuel cladding tubes.

Fuel cladding tubes that have been excessively embrittled due to reactions with steam caused by ineffective safety functions may break or fracture when stressed by thermal shocks or mechanical loads resulting from quenching by water injected into the core from the emergency core cooling system or other sources. If the fuel cladding tubes are broken or fractured, coolable geometry of core is lost, which may lead to core damage. Therefore, it is effective to improve oxidation resistance in high-temperature steam and suppress rupture of fuel cladding tubes in the event of a LOCA as measures for severe accident development.

The introduction of Cr-coated fuel cladding tubes, which has improved high temperature oxidation resistance and, suppress embrittlement and rupture of fuel cladding tubes in the event of an accident, thus being effective in improving the safety of the core and fuel.

(2) Improvement of corrosion resistance during normal operation

During normal operation, fuel cladding tubes are corroded by coolant water. The thickness of the metal part of a fuel cladding tube decrease with corrosion, and a part of hydrogen generated by corrosion is absorbed by it, which causes the hydrogen embrittlement of the fuel cladding tube. This is one of the issues for the advancing core operation. Therefore, the introduction of Cr-coated fuel cladding tubes, which significantly improves corrosion resistance, is effective for the advancing core operation.

3. Development status of accident-tolerant fuel

MHI is currently conducting various tests to verify the performance of Cr-coated fuel cladding tubes in addition to fuel rod irradiation tests in a research reactor in the US, taking into account the current development status of accident-tolerant fuel in the world. The following sections introduce the performance verification tests of Cr-coated fuel cladding tubes developed by MHI [(2)(3)(4)].

3.1 Fabrication of Cr-coated fuel cladding tubes

MHI has developed a Cr coating technique about 10 μm stably with physical vapor deposition (sputtering) process on the outer surface of Zr-based alloy fuel cladding tubes (**Figure 2**). The Cr-coated fuel cladding tubes fabricated by this technique were subjected to performance verification tests as described in Section 3.2.

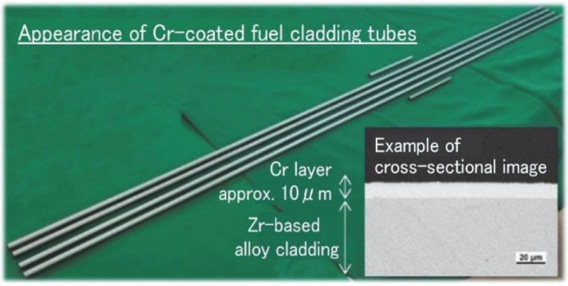

Figure 2 Appearance of Cr-coated fuel cladding tubes and example of cross-sectional image

3.2 Performance verification of Cr-coated fuel cladding tubes

(1) Oxidation resistance at high temperatures

To verify the oxidation reaction of fuel cladding tubes in steam at the high temperature of 1,200°C, which is the upper limit of the acceptable temperature of fuel cladding tubes in the event of LOCA, oxidation tests on outer surface of fuel cladding tubes were conducted. Although the oxidation of conventional Zr-based alloy fuel cladding tubes monotonically increased with oxidation time as shown by the equation in **Figure 3** [(5)], no increase in amount of oxidation was observed in Cr-coated fuel cladding tubes until about 50 minutes (Figure 3).

This is considered as Cr layer effect to suppress the oxidation reaction of the Zr-based material substrate. In addition, as LOCA simulating tests, a pressurized fuel cladding tube burst during temperature elevation, oxidation in steam at the same temperature condition with the oxidation tests then water quenching, were conducted. As results of the tests, Zr-based alloy fuel cladding tubes without Cr coating layer fractured by thermal shock during water quenching, but the Cr-coated fuel cladding tubes survived (**Figure 4**) [(6)]. This is considered that Cr layer suppressed oxidation and embrittlement of the Zr-based material substrate, and thereby the ductility of the Cr-coated fuel cladding tubes was maintained.

These results indicate that the improvement of oxidation resistance of fuel cladding tubes due to Cr layer improves accident tolerance.

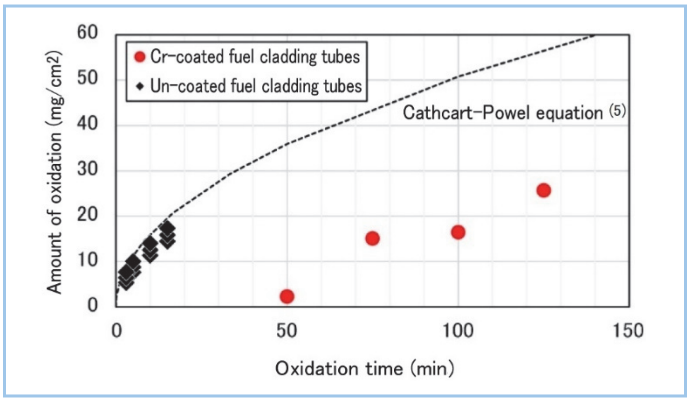

Figure 3 Result of high temperature oxidation test of Cr-coated fuel cladding (1,200°C)

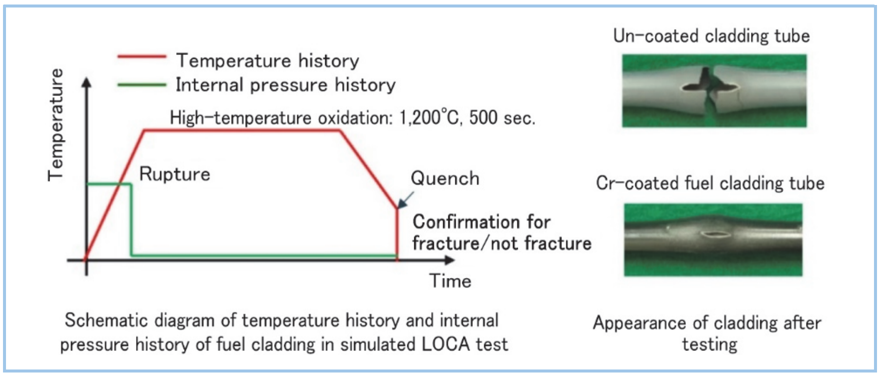

Figure 4 Result of simulated LOCA test of Cr-coated fuel cladding tubes (Test under conditions beyond acceptable amount of oxidation in event of LOCA)

(2) Corrosion resistance during normal operation

We conducted a corrosion test of fuel cladding tubes under primary coolant water condition during normal operation of PWRs. The testing temperature was set to 360°C, which is higher than the coolant temperature during normal operation, for acceleration test of corrosion behavior. After a total of 335 days of the corrosion test, no significant increase in amount of corrosion of Cr layer on outer surface of the Cr-coated fuel cladding tubes was observed (**Figure 5**). Thus, the corrosion test results indicate that Cr layer improves the corrosion resistance of fuel cladding tubes during normal operation, and it leads to suppression of the increase in amount of corrosion, which is one of the issues for the advancing core operation.

Using Cr-coated fuel cladding tubes significantly improves the corrosion resistance of fuel cladding tubes during normal operation, the hydrogen absorption of fuel cladding tubes also decreases. Since it is suggested that the increase in hydrogen absorption of fuel cladding tubes decreases the mechanical strength at high temperature, which causes rupture of fuel cladding tubes at lower stresses in the event of a LOCA [7]. Therefore, Cr-coated fuel cladding tubes are less likely to decrease the rupture stress even in high burnup, which leads to suppression rupture of fuel cladding tubes during LOCA.

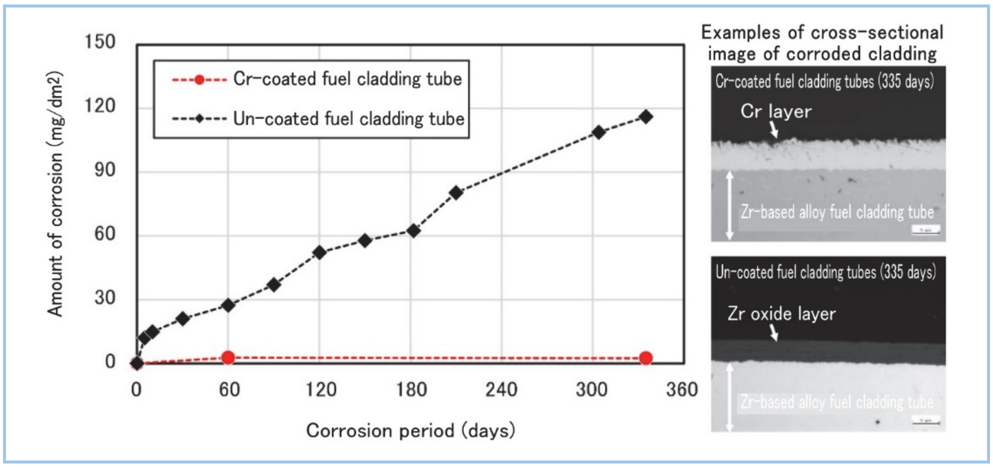

Figure 5 Result of Cr-coated fuel cladding tubes corrosion test under simulating PWR primary coolant condition

3.3 Future plans and prospects

(1) In the current (i) fundamental technology development phase, data evaluation from various tests to understand the performance of Cr-coated fuel cladding tubes under accident and normal operation conditions, and irradiation test data at the research reactor ATR in the United States under Japan-US cooperation, have been conducted for earlier implementation of Cr-coated fuel cladding tubes. Based on findings from them, establishment of evaluation methods for fuel integrity evaluation and core/fuel safety evaluation at actual plants in Japan will be proceeded.

(2) In the (ii) implementation study phase, based on the standard which is being studied by the Atomic Energy Society of Japan that defines the requirements for lead irradiation in a commercial reactor, lead irradiation of a small number of fuel rods using Cr-coated fuel cladding tubes in Japanese commercial PWR will be planned, and evaluation methods are established using the data obtained in the lead irradiation program.

(3) Using the established evaluation method, applicability of Cr-coated fuel cladding tubes to commercial PWR is verified, aiming to eventually enable its implementation to commercial PWRs in the 2030s.

4. Conclusion

We are developing accident-tolerant fuel by applying Cr coating to proven Zr-based alloy. At this moment, through irradiation tests in a research reactor in the United States in addition to various tests to confirm the performance of Cr-coated fuel cladding tubes to verify the effects by using them on the improvement of safety of the core and fuel in the event of an accident and on the improvement of corrosion resistance during normal operation is in progress.

In the future, we will work for lead irradiation of a small number of fuel rods in Japanese commercial PWRs, and following technological development to bring the accident-tolerant fuel to practical use in commercial PWRs, with the aim of achieving the improvement of the safety and advancing core operation in PWRs.

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