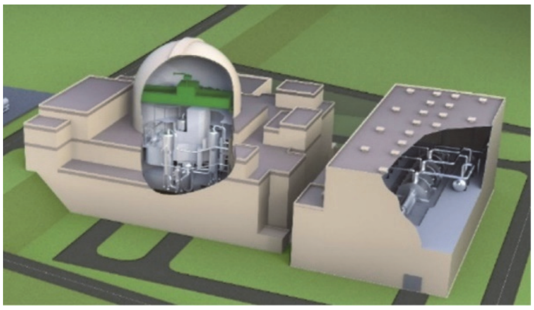
Power Maneuvering Method to Enhance Compatibility with Renewables and Core Design to Improve Pu Utilization for Advanced Light Water Reactor SRZ®-1200



KENTA SHIMIZU[*1] **MASAYUKI KAUCHI**[*1]
SHOHEI OTSUKI[*2] **KOSUKE HIRAMATSU**[*2]

In the construction of a new nuclear power plant, the first requirement is to improve safety and reliability than existing plants. In addition, new operational needs have arisen, including the capability to flexibly adjust output power according to fluctuations in the generation of energy from renewable power sources, and enhanced ability to contribute to the nuclear fuel cycle and energy security. Given these conditions, Mitsubishi Heavy Industries, Ltd. is seeking to achieve more flexible output power adjustment for the new light-water reactor model SRZ-1200 currently under development compared to previous models and is developing technologies that can increase the use of plutonium. While safety is the non-negotiable first priority, development of a nuclear power plant with enhanced operability is another way that contributes to increased public acceptance of the construction of a new plant and the continued use of nuclear energy.

1. Introduction

In the development of the advanced light-water reactor SRZ-1200, Mitsubishi Heavy Industries, Ltd. (hereinafter referred to as MHI) is considering whether to adopt two technologies to improve operability. The first technology under consideration is to improve performance of flexible power operations (hereinafter referred to as FPO). Nuclear power plants are used as base-load power sources that can stably supply electricity day or night, regardless of the season. However, as the ratio of the generation of energy from renewable power sources (hereinafter referred to as "renewable power generation") is expected to further increase, maintaining balance in electricity supply and demand will become even more difficult in the future. Improving FPO performance of a nuclear power plant to stabilize the power grid is one method that has gained attention. The second technology under consideration is to increase the amount of plutonium used in the "*Plu-thermal*" project, in which MOX fuel is used in a light-water reactor. Under Japan's national policy of not possessing plutonium without specific purposes, plutonium supply and demand should be balanced. Consequently, increasing the MOX fuel loading in the reactor core is needed.

Efforts to improve the FPO performance and increase the amount of plutonium used are each introduced as follows.

2. Flexible power operation (FPO) of nuclear power plant

Currently nuclear power plant is used as a base-load power source in Japan, whereas thermal power generation is mainly used to balance supply and demand. However, with the recent increase in renewable power generation, inadequacy of Japan's current system to balance the power grid has become apparent, despite the need to further reduce the use of fossil fuels as the adjustment power source in order to achieve carbon neutrality. Regarding existing nuclear power plants, past demonstration tests using actual units have confirmed FPO capability under conditions with a variable output range of ±50% and a output change rate of ±0.28 %/min. If a nuclear power plant is to proactively balance electricity supply and demand, enhancing the capability to adjust output power is essential. Since the power source of nuclear power generation is not dependent on fossil fuels, ways to improve FPO performance have gained attention. One challenge with SRZ-1200 therefore

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[*1] Engineering Manager, Reactor Core & Safety Engineering Department, Nuclear Energy System
[*2] Reactor Core & Safety Engineering Department, Nuclear Energy System

lies in enhancing output power adjustment capability to achieve advanced FPO. The following section describes the technological developments to improve FPO performance.

2.1 Output power control mechanism for Pressurized water reactors

In Pressurized Water Reactor (PWR), output power is adjusted by the rate of steam flowing into the turbine. The primary system of the PWR is separated from the secondary system by the steam generator (SG), mitigating the effects on the primary system due to changes in steam flow rate caused by changes in the turbine load. Taking advantage of this characteristic, a control mechanism for “reactor output following the turbine load” has been adopted on PWRs. When change in the steam flow rate causes the temperature of the primary system to reach a level requiring the control system to be activated, control rods are automatically inserted or withdrawn to adjust the average temperature of the primary system coolant, and reactor output follows the turbine load. PWRs in Japan are designed to operate continuously as long as change in turbine load remains within the following ranges and does not activate the reactor trip (**Figure 1**):

- ±10% step load change
- ±5 %/min ramp load change
- Significant step load drop (e.g., by 50% or 95%)

PWRs in Japan have the capability to respond to the above-mentioned load changes. Therefore, stability of the power grid while continuing operation can be maintained, even if a grid disturbance leads to a change in turbine load. Moreover, as in the case of daily load-following, which is described later, output power can also be adjusted during operation in order to balance supply and demand.

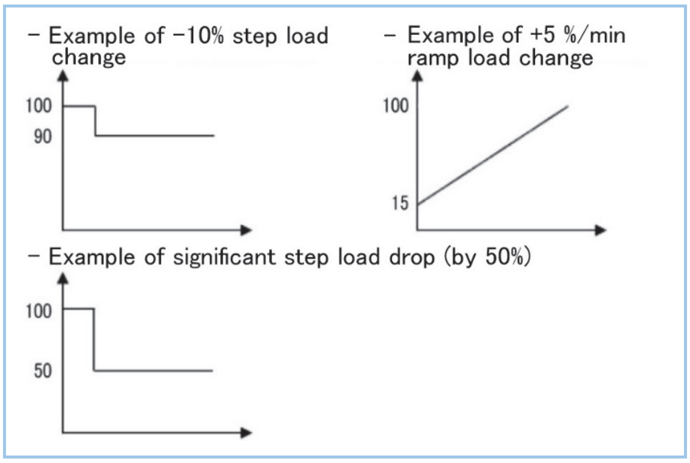

Figure 1 Example of load changes which can be handled by PWRs in Japan

2.2 FPO performance of current PWRs

Output power of PWRs is adjusted by either using a control rod drive mechanism or changing the boron concentration in the primary cooling water. Turbine load is adjusted according to change in power demand. The control rods are then inserted or withdrawn according to change in turbine load. As a result, reactor output is automatically controlled. However, this method to adjust output power affects neutron flux levels in both the upper and lower parts of the core, and as a result the axial power distribution deviation (ΔI), which is the difference between the upper and lower core neutron flux levels, changes. The ΔI value must remain within a predetermined range during operation for safety reasons. Therefore, it is necessary to adjust the position of the control rods before ΔI falls outside the target range. Fluctuations in power demand during the day and night, as well as fluctuations due to renewable power generation, require changing the power generation load accordingly. Power plants adjust generator output to balance supply and demand (daily load-following operation). However, as described later, when the conventional control rod drive mechanism is employed in an existing plant, there are limitations on the variable output range and the output change rate due to the need to maintain the ΔI value within the predetermined range. Thus, daily load-following remains operable under conditions with a variable output range of ±50% and an output change rate of ±0.28 %/min.

2.3 Enhancement of FPO performance

The ratio of renewable power generation is expected to further increase by the time SRZ-1200 starts operation. Technical development to realize advanced FPO in connection with SRZ-1200 has progressed. Here, the performance of daily load following operation is explained on various aspects of FPO. SRZ-1200 aims to achieve a variable output range of ±70% and an output change rate of ±3 %/min, which is an increase from ±50% and ±0.28 %/min, respectively, of current plants. The improved control rod drive system, which is one technology adopted for enhanced FPO performance, is summarized below.

As described in Section 2.2, reactor output must be controlled so the ΔI value remains within the target range during daily load-following operation. For existing plants in Japan, as mentioned in Section 2.1, average temperature of the primary system coolant is adjusted to control reactor output according to changes in turbine load. In the conventional control rod drive mechanism, the position of the control rods is controlled according to a fixed sequence, where "the control rod banks are moved in a predetermined order" and "each control bank is moved to maintain the distance from the control rods that have already been moved." With this mechanism, when the tips of control rods are in the lower or upper parts of the core, changing ΔI to the target value is difficult as further insertion/withdrawal of these control rods in the same direction can affect neutron flux levels in both the upper and lower parts (**Figure 2**). Therefore, in order to ensure that the ΔI value does not exceed the target range, ΔI is controlled by changing the boron concentration so the temperature of the primary system reaches a level to activate the control rod control system and change the position of the control rods. However, as boron concentration is regulated by the chemical volume control system, there is a time delay before core reactivity is affected. In cases of load change patterns with a large change in variable output range and output change rate, this time lag may result in failure to maintain ΔI within the predetermined range.

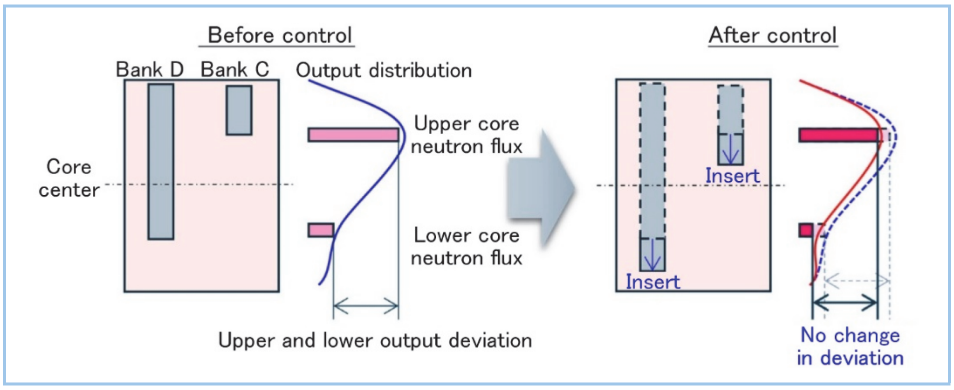

Figure 2 Control rod drive system in existing plants

Consequently, the control rod drive system of SRZ-1200 has been improved, and a control rod drive system that can control reactor output so the control rods can maintain ΔI within the predetermined range is under development. The control method of this improved control rod drive system is shown in **Figure 3**. Unlike conventional mechanisms with a fixed sequence, this new control rod drive system can flexibly select which control rod is moved based on its position and change in ΔI value. Each control rod moves independently regardless of whether its tip is located in the upper or lower section of the core. In this new control method, average temperature of the primary system coolant is controlled by the direction in which the control rod is moved (i.e., insertion or withdrawal); the control rod that can minimize the change in the ΔI value is selected.

The effect of this improved method was confirmed by analysis. Analysis results are shown in **Figures 4 and 5**. As shown by the turbine load on the left y axis in Figure 4, the assumed load-following operation in this analysis follows the 18/6 pattern (dividing one day (24 hours) into two parts: 18 hours for rated output, and 6 hours for partial output), where the output can change from 100% to 30% in the improved control rod drive system. Effect of this improved method is shown for a period of partial output maintained for 6-hours. In the conventional method, D and C banks were moved simultaneously, but in the improved method, C bank is independently driven. In the conventional method, maintaining ΔI within the target range is difficult and as a result, responding to the FPO for this load change pattern is also difficult. On the other hand, in the developed improved method, capacity of the control rods is maximized during output power adjustment so ΔI value can be maintained within the targeted upper and lower limits. Advanced FPO has thus been made possible.

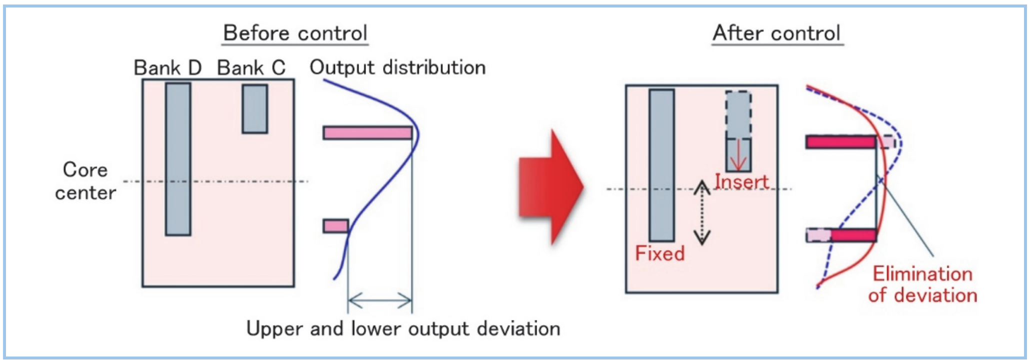

Figure 3 The improved control rod drive system for SRZ-1200

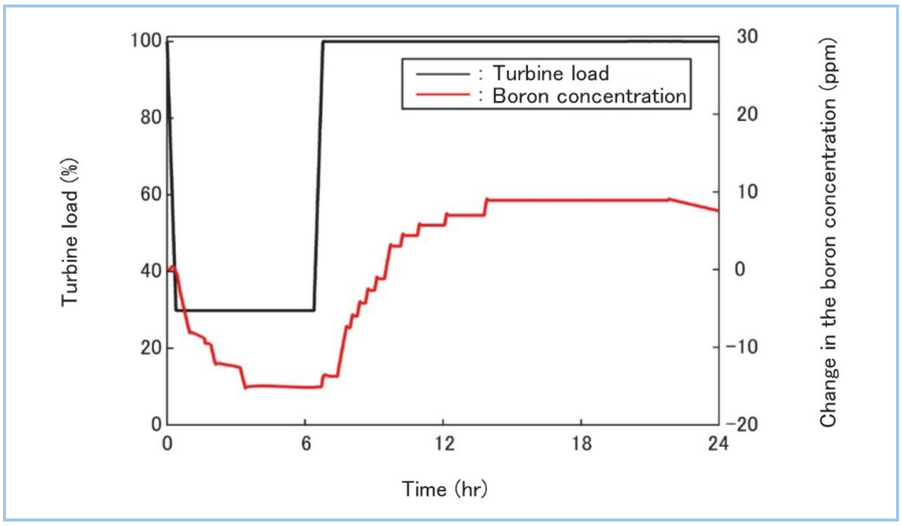

Figure 4 FPO assessment results for the improved control rod drive system

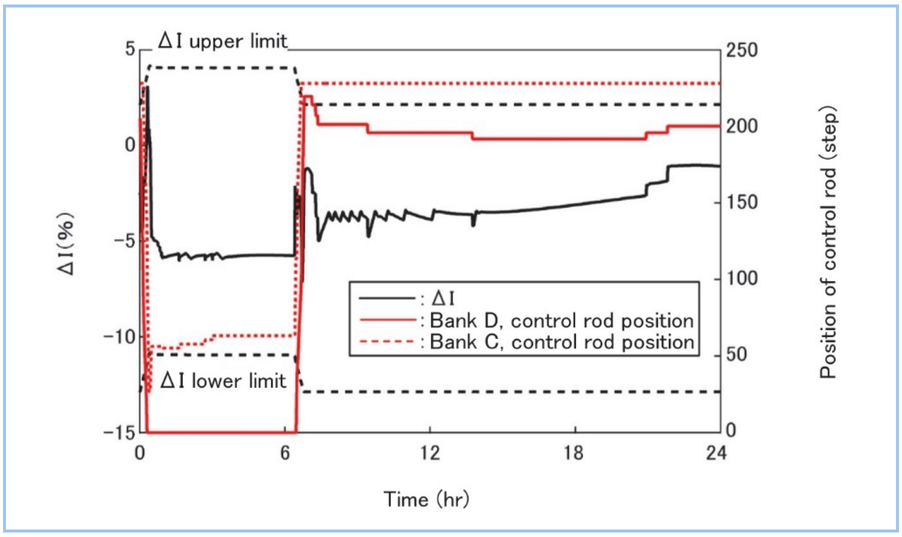

Figure 5 FPO assessment results for the improved control rod drive system

3. Increased plutonium consumption

In order to secure future energy supply, Japan seeks to achieve a “nuclear fuel cycle” where uranium and plutonium extracted from spent fuel are reused as fuel. Under Japan’s national policy of “not possessing plutonium without specific purposes,” the *Plu-thermal* project to use MOX fuel in light-water reactors is underway. At present, the ratio of MOX fuel loaded in a PWR core is assumed to be approximately 1/4 to 1/3. To contribute to this project, MHI has been developing technologies to increase plutonium consumption capability.

In this chapter, regarding technologies to increase the amount of plutonium used in the *Plu-thermal* project, design of an improved MOX fuel assembly is discussed in Section 3.1 and a technical consideration of a “full MOX core” (where only MOX fuel assembly is loaded into the reactor core) is presented in Section 3.2.

3.1 Improved MOX fuel assembly

The MOX fuel assembly applied to current PWRs is comprised only of MOX fuel rods with three different levels of plutonium and no uranium fuel rods (**Figure 6**). When compared to uranium, plutonium tends to absorb more thermal neutrons, and the number of thermal neutrons in a MOX fuel-loaded core is less than that of a uranium core. As a result, the control rods reactivity worth (indicating the effectiveness of the control rods when inserted) tends to be smaller. In current PWR operations, the ratio of MOX fuel assemblies loaded in the core remains at approximately 1/4 to 1/3, with the remaining filled with uranium fuel assemblies. The plutonium content in the outermost layer of the MOX fuel assembly is lower in order to prevent power peaking by thermal neutrons supplied by the adjacent uranium fuel assemblies.

On the other hand, this improved MOX fuel assembly contains uranium fuel rods (**Figure 7**), which is easy to secure the control rods reactivity worth when inserted. Thus, the ratio limit of MOX fuel assemblies loaded into the core, which has been set to ensure shutdown capability, is no longer needed. Moreover, when fully loaded with MOX fuel assemblies, the precautionary measure to partially reduce plutonium content in the outermost layer mentioned above is not needed, and as a result, it is possible to increase the total amount of plutonium used.

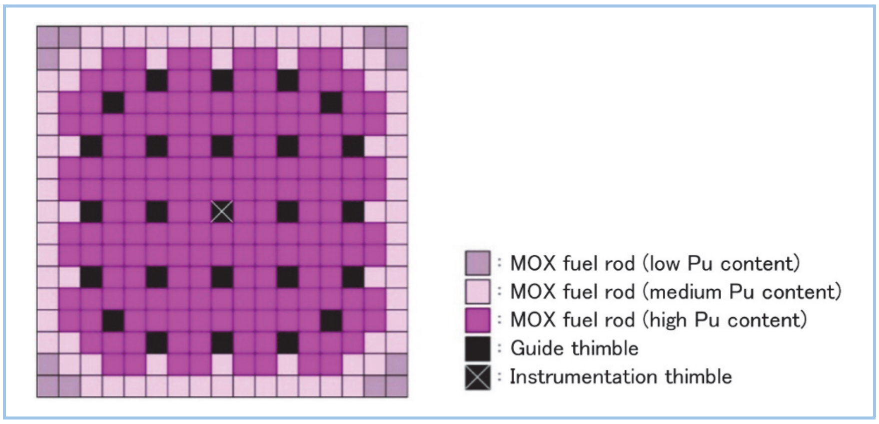

Figure 6 Conventional MOX fuel assembly for PWRs

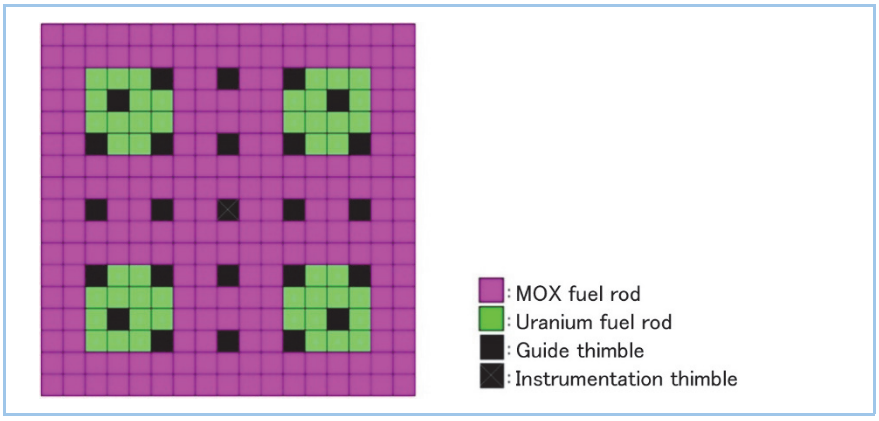

Figure 7 A configuration example of the improved MOX fuel assembly

3.2 Full MOX core

The MHI neutronics design code system Galaxy/Cosmo-S(1) was used to assess the nuclear parameters of the core when fully loaded with the aforementioned improved MOX fuel assemblies based on the configuration of SRZ-1200 (193 fuel assemblies and 57 control rod clusters). In this assessment, the Advanced RCCA (Rod Cluster Control Assembly)(2) in which a part of neutron absorber consists of B4C is used.

The fuel loading pattern used in the core analysis is shown in **Figure 8**. As described in Section 3.1, a major challenge in loading MOX fuel is to decrease the reactivity worth of the control rods and to increase the local power peaking. Assessment results are described as follows.

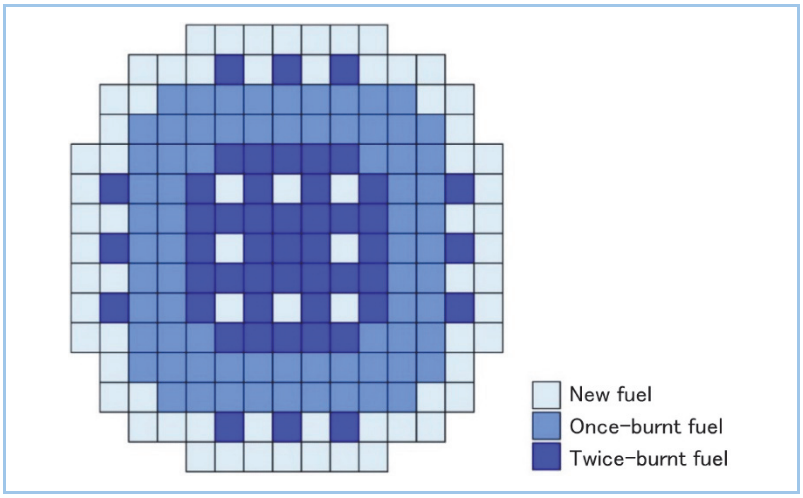

Figure 8　A loading pattern example of full MOX core

(1)　Reactor shutdown margin (indicates the degree of margin taken in order to achieve "subcriticality")

The value obtained in this assessment was 3.3 %Δk/k, which satisfies the design target of 1.6 %Δk/k. In other words, a full MOX core with the improved MOX fuel assemblies has sufficient shutdown capability.

(2)　Radial power peaking factor ($F_{\Delta H}{}^{N}$)

The radial power peaking factor ($F_{\Delta H}{}^{N}$) change in accordance with the cycle burnup is shown in **Figure 9**. As can be seen here, a core design without excess power peaking is possible by fully loading the core with the improved MOX fuel assemblies.

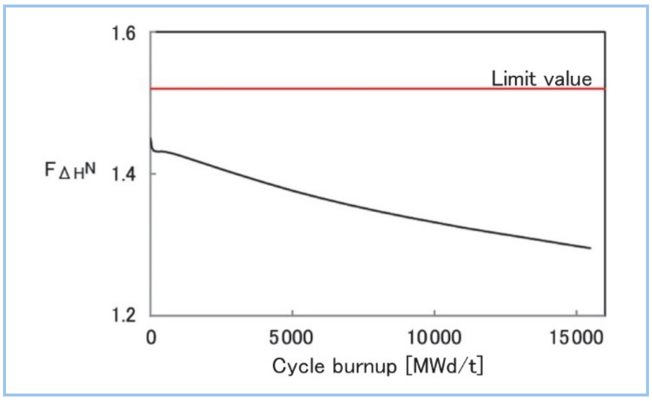

Figure 9　Example of assessment of radial power peaking factor

3.3　Amount of fissile plutonium used

In the full MOX core shown in Figure 8 the annual consumption of fissile plutonium (Pu-f) is approximately 0.38 t/GW/year. Compared to a case with 1/4 loading of conventional MOX fuel assemblies (annual consumption of Pu-f is about 0.13 t/GW/year), this is approximately three times the amount.

4. Conclusion

In this report, efforts in the technical development of SRZ-1200 by MHI to improve operability were described. Enhancing FPO performance by improving the control rod control system, specifically increasing the variable output range from ±50% to ±70% and the output change rate from ±0.28 %/min to ±3 %/min, is planned. Moreover, the Pu consumption can be increased to almost 3 times the current amount by employing the improved MOX fuel assemblies. In line with the government's efforts toward carbon neutrality, MHI will continue to contribute to the effective use of nuclear power generation against the backdrop of a diversified power supply mix, and seek to develop technologies that promote stable power supply in Japan.

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