APPLICATION OF TRANSIENT FUEL ROD PERFORMANCE CODE FRAPTRAN FOR SFP-LOCA TEST

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ABSTRACT

Extensive understanding of the fuel behavior during spent fuel pool (SFP) accidents is a crucial issue for the safety analysis of nuclear power plants. Compared with the loss of coolant accident (LOCA) conditions in a reactor, those of LOCA in an SFP are mainly characterized by the much lower rate of temperature increase and a larger pressure difference between inside and outside of the fuel rod. Since these conditions affect the fuel rod deformation behavior, a numerical simulation using the transient fuel rod performance code FRAPTRAN and an experiment comprising an unirradiated cladding burst test were conducted to clarify the basic mechanism of the cladding burst behavior under SFP-LOCA conditions, in which a simulated fuel rod sample was heated at a rate of 0.0056 °C/s until the cladding burst. It was observed that the ballooning of the cladding occurred at the position with the highest temperature and that the cladding ruptured at this position in both the experimental and simulation results. The calculated cladding temperature was in reasonable qualitative agreement with that in the experiment. It was found by sensitivity analysis using FRAPTRAN that the burst temperature is affected by the rate of temperature increase, the inner pressure of the fuel rod, and the temperature in the plenum region.

1. Introduction

The accident at Fukushima Daiichi nuclear power plant in Japan confirmed the robustness of the spent fuel pol (SFP) but also reaffirmed that an accident at the SFP is a crucial issue that might ultimately lead to the release of radionuclides in the reactor building. The Japanese nuclear regulatory authorities requested suppliers to formulate countermeasures for cooling facilities and mitigation equipment in the case of an accident involving the loss of cooling water or the loss of cooling function. To evaluate the fuel-cooling performance of the countermeasures, it is necessary to understand the fuel behavior in detail during SFP accidents for the safety analysis of nuclear power plants and probabilistic risk analysis.

A loss of coolant accident (LOCA) in SFPs is an important event to be evaluated, where the pool water inventory is lost owing to an SFP pipe failure, the loss of SFP gate integrity, or any other reason [1]. If no measures are taken during SFP-LOCA, the used fuel rods begin to be uncovered, balloon, and then burst with the release of radioactive nuclides. Therefore, from the viewpoint of safety analysis, the burst criteria of the fuel rods should be clarified and predicted accurately. Numerical simulations of SFP-LOCA have been conducted using severe accident evaluation codes such as MAAP [2] and MELCOR [3] to investigate the thermal and mechanical responses during the entire SFP-LOCA scenario. In both codes, the burst of the fuel cladding is set to be triggered when the cladding temperature exceeds a prescribed value for both SFP and reactor events, where the default temperature is 1000 K in MAAP [4] and 1173 K in MELCOR [5]. These temperature criteria were developed on the basis of extensive experimental results for cladding burst tests conducted under in-reactor LOCA conditions. On the other hand, some conditions of SFP-LOCA are different from those of in-reactor LOCA, such as the lower rate of temperature increase due to the lower decay heat and the larger pressure difference between the inside and outside of the cladding. Hence, the deformation and burst behavior of the cladding in SFP-LOCA should be investigated taking these characteristic conditions into consideration.

Existing cladding burst data are summarized in the literature [6] as the time, temperature, hoop stress, hoop strain, or pressure at burst. However, most of the tests were conducted with a larger rate of temperature increase than that under the SFP-LOCA conditions. Hence, few data have been obtained on the deformation of used fuel during the SFP-LOCA. In this study, a numerical simulation is conducted to clarify the basic mechanism of the cladding burst behavior under SFP-LOCA conditions. The transient fuel rod performance code FRAPTRAN [7] is used. An experiment is also conducted under similar conditions using the test apparatus DEGREE [8] and the result is compared with that obtained by FRAPTRAN. In addition, a sensitivity analysis is conducted for several parameters to investigate their effect on the burst criteria.

2. Cladding burst test under SFP-LOCA conditions

2.1 Description of the test

To investigate the deformation and burst behavior of the used fuel rod under SFP-LOCA conditions, a numerical simulation and an experiment comprising a cladding burst test were conducted. In the cladding burst test, a sample of a simulated fuel rod was prepared, which was pressurized internally to simulate the increased inner pressure of an irradiated PWR fuel rod due to the release of fission gas from pellets. The sample was heated at a constant rate of temperature increase until it burst under atmospheric pressure to measure the cladding burst temperature and inner pressure.

2.2 Numerical simulation

2.2.1 FRAPTRAN settings

A numerical simulation of the cladding burst test was conducted using the computer code FRAPTRAN-2.0, which was developed to calculate the temperature and deformation history of a fuel rod as a function of the time-dependent fuel rod power and coolant boundary conditions. In this study, the FRACAS-I model [7,9] was used to evaluate the cladding deformation, in which the stress-induced deformation of the fuel pellets is ignored and the axisymmetric deformation of the cladding is evaluated under a thin-wall assumption. The BALON2 model [10] was used for the cladding burst criteria, which predicts failure in the cladding when either local true hoop stress or strain exceeds an empirical limit that is a function of temperature. The other input parameters are given in the following subsections.

2.2.2 Configuration of the fuel rod sample

Representative input parameters are shown in Table 1. The outer diameter and thickness of the cladding are set to 9.5 mm and 0.57 mm, respectively. The type of cladding was set to Zircaloy-4, the physical properties of which are calculated using the MATPRO model [11] equipped in the code. The axial length and diameter of the pellets are 200 mm and 8.2 mm, respectively. Instead of defining the axial length of the cladding, the volume of the plenum gas was set as 1.5×10^4 mm^3 in accordance with the FRAPTRAN code. The plenum gas volume includes both the volume of the actual plenum part in the sample and that of the stainless-steel pipe connected to the sample to provide the filling gas, which is used in the experiment described in section 2.3. The internal pressure was set to 8.0 MPa at room temperature and the filling gas was helium. The effects of irradiation on the chemical and mechanical properties of the cladding, such as the zirconium oxide thickness, residual strain, and hydrogen absorption, were omitted in this calculation. The effects of irradiation on the pellets such as swelling or a high-burnup structure were also omitted.

Although the decay heat of the spent fuel is the main heat source causing the temperature rise of the fuel rods in the SFP-LOCA scenario, the decay heat was set to zero in this calculation. Instead, the temperature history of the coolant is given as an input so that the cladding temperature follows the desired history by the heat transfer from the coolant to the cladding as described in subsection 2.2.3.

	Numerical simulation (FRAPTRAN)	**Experiment (DEGREE)**
Fuel rod configurations		
Cladding diameter	9.5 mm	9.5 mm
Cladding thickness	0.57 mm	0.57 mm
Cladding length	-	235 mm
Cladding type	Zircaloy-4	Zircaloy-4
Plenum volume	1.5×10^4 mm^3	1.5×10^4 mm^3
Pellet diameter	8.2 mm	8.2 mm
Fuel stack	200 mm	200 mm
Initial pressure P_0 at room temperature	8.0 MPa gage	8.0 MPa gage
Rod average power (Decay heat)	0 W/m	-
Initial oxide thickness	0 μm	As received
Initial hydrogen absorption	0 ppm	As received
Gas cooling conditions during LOCA		
Heat transfer coefficient at cladding surface	2500 $W/K/m^2$	-
Coolant gas	-	Steam-50 vol.% Air
Flux	-	4.8 $g/s/cm^2$
Pressure	Atmospheric pressure	Atmospheric pressure
Rate of temperature increase	$\frac{dT}{dt} = 5.6 \times 10^{-3}\ ℃/s$ (coolant)	$\frac{dT}{dt} = 5.6 \times 10^{-3}\ ℃/s$ (measured at cladding)

Tab 1: Parameters used in the FRAPTRAN calculation and the DEGREE experiment

2.2.3 Air cooling condition during LOCA

An air-containing atmosphere at atmospheric pressure is one of the characteristic conditions in SFP-LOCA. However, no models for an air-containing atmosphere have been prepared in the FRAPTRAN code because SFP-LOCA is not a specific target of the code. In this study, the air-cooling condition was simulated by setting the coolant pressure to that of the atmosphere without explicitly defining the type of coolant fluid. The coolant temperature was rapidly increased to 490 °C and then the rate of temperature increase was fixed to 0.0056 °C/s. The initial rapid temperature increase to 490 °C was to shorten the total test period under the assumption that no significant events occur below 490 °C. The rate of 0.0056 °C/s (=20 °C/h) was considered to be typical under SFP-LOCA conditions on the basis of the result of an SFP-LOCA simulation conducted using the MAAP code [2]. The heat transfer coefficient between the cladding surface and the coolant was set to 2500 $W/K/m^2$, which is sufficiently high for the cladding temperature history to be almost the same as that of the coolant. Although several chemical reactions (oxidation of the cladding surface, hydrogen absorption, nitrogen-induced breakaway, and so forth) might occur on the cladding surface under the SFP-LOCA conditions, their effect was not considered in this simulation.

2.2.4 Plenum gas temperature model

There are several models prepared in FRAPTRAN to calculate the plenum gas temperature. In this simulation, the temperature of the plenum gas was kept constant at room temperature during the whole test period. This is the same as assuming that the plenum part of the fuel rod is sufficiently cooled by heat exchange with the air naturally circulating around the fuel rod and that the volume of the plenum gas is much larger than the gas volume in the active fuel part including the pellet dish, chamfer, and pellet-cladding gap. The validity of this assumption is discussed in section 4.4.

2.3 Experiment

An experiment was conducted under similar conditions to the simulation using the degradation and relocation test equipment known as DEGREE [8,12]. The structure of the apparatus is illustrated in Figure 1. The main test conditions are summarized in Table 1.

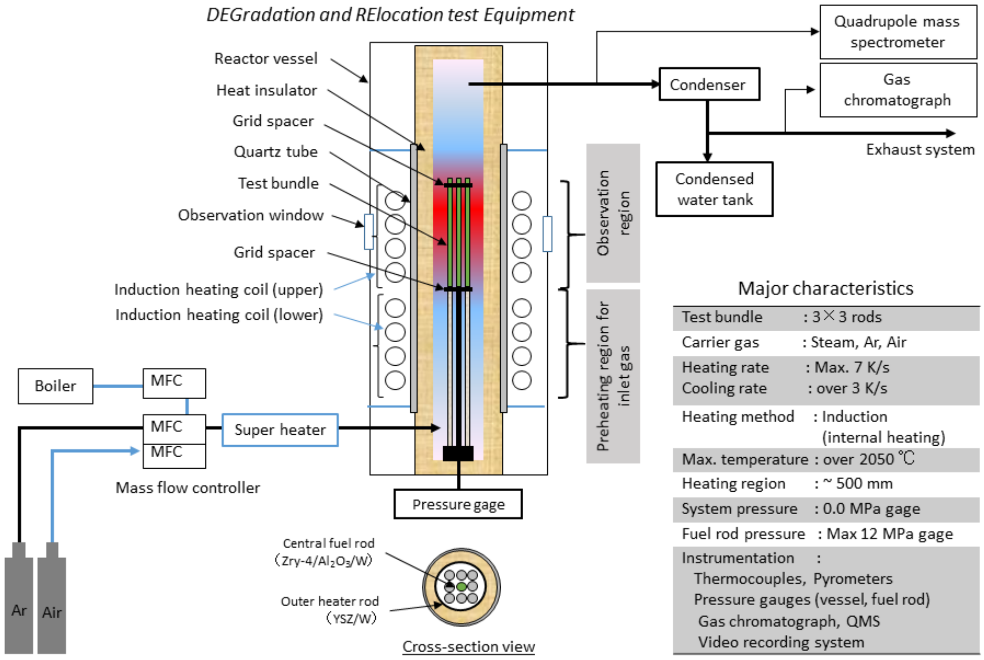


Fig 1. Structure and performance of test apparatus DEGREE

A 17 × 17 type Zircaloy-4 cladding tube (235 mm in length, as received) was used. Annular alumina pellets of 8.2 mm outer diameter and 5.7 mm inner diameter were loaded into the cladding tube as simulated fuel pellets, along with a tungsten rod of 5.5 mm diameter as a heating element (susceptor) to simulate internal heating. The cladding tube was sealed by tungsten inert gas (TIG) welding with a Zircaloy-4 end plug. Stainless-steel piping was connected to one end plug of the sample to fill the internal gas and monitor the pressure changes during the test. Eight heater rods (yttria-stabilized zirconia-clad tungsten rods) were placed around the self-standing test sample assembled as 3 x 3 upper and lower support grids. The fuel pitch was set to 12.6 mm.

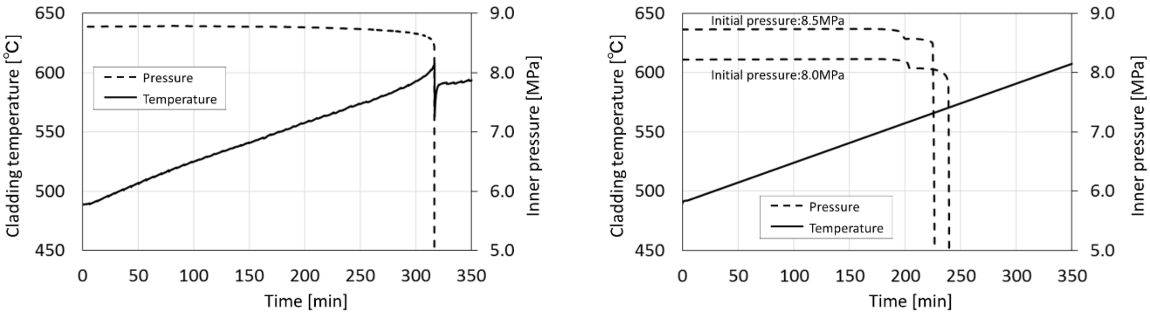
The surface temperature of the cladding was measured by fixing a Pt-13%Rh/Pt-type thermocouple (R-type) at two circumferential positions located at two different heights slightly apart from the highest-temperature section of the sample. Using the axial temperature distribution of the fuel rod sample measured in advance under the same conditions without internal pressurization, the cladding temperature at the burst portion at the time of burst was evaluated.

The sample was pressurized internally up to 8.0 MPa (gage) with helium gas (99.9999% purity) at room temperature before the test. This internal pressure value envelops the scattered internal pressure data of current high-burnup fuels. A steady-state condition was maintained at about 490 °C to confirm the operation of the instrumentation system and to stabilize the inside of the test equipment in the steam-air mixture flow. This temperature is considerably lower than the creep strain initiation temperature of Zircaloy-4. Thereafter, in a mixture flow of steam-50 vol% air having a steam flux of 4.8 g/s/cm^2, the sample was heated inductively at a heating rate of 0.0056 °C/s until it burst. The burst timing of the cladding was determined from the detection of helium gas by the quadrupole mass spectrometer located at the exhaust system and the internal pressure drop recorded by the pressure gage connected to the sample. About 6 h after the burst, the heating was turned off, and at the same time, the supply of steam and air was switched to argon gas and furnace was cooled.

3. Results

The inner pressure and cladding temperature are shown in Figure 2(i), which were measured in the experiment. The inner pressure remained almost constant at 8.7 MPa for the first 250 min. Then the pressure slightly decreased from 250 min to 320 min because the internal volume of the sample increased owing to the large plastic deformation of the cladding that occurred locally at the highest-temperature position. This local large deformation is referred to as ballooning. Finally, the pressure abruptly decreased at 320 min, which indicates that the cladding burst at the ballooning position and the inner gas was released. The appearance of the burst position is shown in Figure 3. The result of the FRAPTRAN calculation is shown in Figure 2(ii). Similarly to the experimental result, the inner pressure remained almost constant during most of the temperature-increase phase, then a small drop in the pressure was observed, and the cladding finally burst as indicated by the large drop in the pressure. The simulation and experimental results are summarized in Table 2. It is reasonable to conclude that the FRAPTRAN calculation well reproduced the deformation and burst behavior of the sample under the SFP-LOCA conditions because the results were in qualitatively good agreement.

However, the internal pressure during the temperature-increase phase was underestimated by FRAPTRAN (P=8.2 MPa) compared with the experimental result (P=8.7 MPa) because the plenum gas was kept at room temperature in the simulation, whereas there might have been a small increase in the temperature of the plenum gas in the experiment. Therefore, another FRAPTRAN calculation was conducted in which the initial inner pressure P_0 was increased from 8.0 MPa to 8.5 MPa so that the pressure history in the simulation agreed with the experimental result, which is also shown in Figure 2(ii). In both simulation results, the burst temperature was lower than that in the experiment. In the BALON2 model, which gives the burst criteria in FRAPTRAN, the cladding burst is initiated when either the local hoop stress or strain in the cladding exceeds the limit value, which is a function of the temperature. The limit values were obtained on the basis of experiments conducted under the conditions simulating the LOCA in the reactor core at temperatures of above 700 °C [7]. Hence, the criteria for the burst occurring at lower temperatures are obtained by simply extrapolating these data. This is considered to be one of the reasons for the underestimation of the burst temperature in this simulation. The accumulation of experimental burst data under SFP-LOCA conditions is necessary to improve the accuracy of the burst criteria, which is left as future work.



(i) experimental (ii) simulation

Fig 2. Pressure and cladding temperature histories measured in (i) the experiment and (ii) the FRAPTRAN calculation

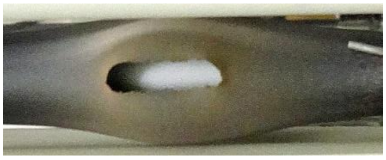


Fig 3. Appearance of the cladding burst

	DEGREE experiment	FRAPTRAN calculation	
		P_0=8.0MPa	P_0=8.5MPa
Burst temperature [°C]	617	572	567
Internal pressure in final minute before cladding burst [MPa gage]	8.4	8.0	8.5
Maximum pressure [MPa gage]	8.7	8.2	8.7

Tab 2: Burst conditions obtained by experiment and simulations

4. Sensitivity analysis

4.1 Parameters to be studied

As apparently shown by the experimental and simulation results, the large pressure difference between the inside and outside of the cladding is one of the main driving forces for the cladding deformation, which implies that the inner pressure of the fuel rod affects the burst conditions. The temperature of the plenum gas is also a key parameter for the cladding burst because the inner pressure of the fuel rod is dependent on the plenum gas temperature. The cladding burst temperature obtained in our test was lower than those in an in-reactor LOCA [6], where the cladding burst generally occurs above 700 °C. The lower rate of temperature increase might have contributed to the lower burst temperature because the cladding was exposed to the outward pressure for a longer time and the accumulation of creep strain was larger than that in the case of an in-reactor LOCA. Hence, the rate of temperature increase is also an important parameter affecting the cladding burst behavior.

To evaluate the effects of these parameters, FRAPTRAN calculations of the cladding burst test were conducted for three cases, as shown in Table 3. The conditions of the test described in section 3 are referred to as the base case which is used for comparison.

	Base case	Case 1	Case 2	Case 3
Rate of temperature increase [°C/s]	0.0056	0.0056 – 5.0	0.0056	0.0056
Initial inner pressure [MPa]	8.0	8.0	0.5 – 8.0	8.0
Plenum gas temperature	Constant at room temperature			Increase with cladding temperature

Tab 3: Test parameters employed in the sensitivity analysis

4.2 Effect of the rate of temperature increase (case 1)

In the case 1 calculations, the rate of temperature increase was varied from 0.0056 °C/s to 5 °C/s to investigate its effect on the burst conditions. The highest rate (5 °C/s) simulates typical in-reactor LOCA conditions. The burst temperatures obtained by FRAPTRAN are shown in Figure 4. The burst temperature was lower when the rate of temperature increase was lower. The reason for this is considered to be that the cladding was kept at a high temperature for a longer time in the case of a lower rate of temperature increase and thus a larger creep strain was accumulated.

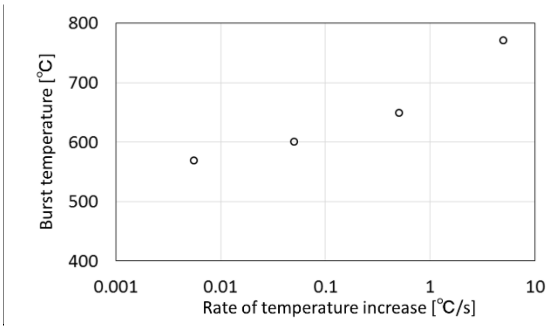


Fig 4. Burst temperature for different rates of temperature increase evaluated by FRAPTRAN (case 1)

The difference in the burst temperature between the SFP-LOCA case (0.0056 °C /s) and the in-reactor-LOCA case (5 °C/s) was approximately 200 °C. This result indicates that the duration of cladding exposure to a high temperature should also be taken into consideration when predicting the cladding burst in SFP-LOCA.

4.3 Effect of the initial inner pressure (case 2)

To investigate the effect of the initial inner pressure, the calculations were conducted with the pressure varied from 0.5 MPa to 8.0 MPa. As shown in Figure 5, the cladding burst occurred at a lower temperature as the initial pressure was increased. The difference in the burst temperature between 0.5 MPa and 8.0 MPa was more than 300 °C. Hence, the inner pressure of the used fuel rod is also considered to be an important parameter to be studied when predicting cladding burst.

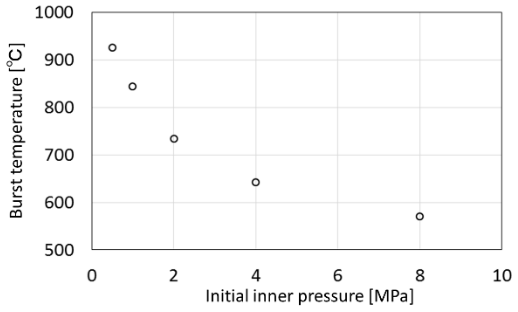


Fig 5. Burst temperature for different initial pressures evaluated by FRAPTRAN (case 2)

4.4 Effect of the plenum gas temperature (case 3)

In the case 3 calculations, it was assumed that the plenum gas is heated without any cooling so that the plenum gas temperature remains equal to that of the cladding and the inner pressure of the cladding increases in proportion to the cladding temperature. The result is compared with that of the base case, where the plenum gas temperature was kept at room temperature. As shown in Figure 6, the pressure in case 3 increased to 20 MPa at the beginning of the temperature-increase phase. Since the inner pressure was larger in case 3, the deformation and burst occurred earlier than in the base case. The temperature and inner pressure at the cladding burst in case 3 were 538 °C and 19.3 MPa, respectively. This result indicates that the cooling conditions of the plenum part of the fuel rod and its volume affect the cladding burst conditions to some extent. The actual conditions should be somewhere between the values for the base case and case 3. Hence, it is necessary to correctly evaluate the plenum cooling conditions by taking into consideration the natural convection of the air around the fuel rods, the heat transfer from the fuel to the plenum gas, and so forth, to enable the quantitative prediction of the cladding burst criteria in SFP-LOCA.

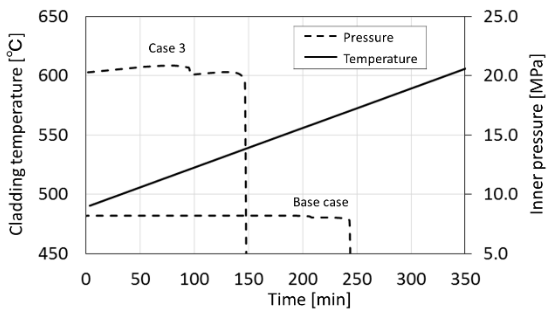


Fig 6. Pressure and cladding temperature histories calculated by FRAPTRAN for the base case (plenum gas temperature is kept at room temperature) and case 3 (plenum gas temperature increases with the cladding temperature)

5. Conclusion

The simulation of a cladding burst test under the conditions anticipated in SFP-LOCA was conducted using the FRAPTRAN code. Although the calculation of the SFP-LOCA conditions was not a specific target of FRAPTRAN, it was enabled by setting the pressure of the coolant to that of the atmosphere and using a low rate of fuel temperature increase to simulate the conditions. The deformation and burst behavior of the cladding were clarified by investigating the simulation results. An experiment using DEGREE was also conducted under similar conditions and its result qualitatively reproduced the simulation result. Therefore, it was confirmed that the FRAPTRAN code is applicable to SFP-LOCA analysis. It was found that a lower rate of temperature increase and larger pressure difference, which are typical characteristics of the SFP-LOCA conditions, result in a lower burst temperature owing to the greater accumulation of creep strain. Sensitivity analysis was also conducted using FRAPTRAN and it was found that the cladding burst temperature is dependent on the rate of temperature increase, the inner pressure of the fuel rod, and the temperature in the plenum region. Hence, it is highly desirable to accumulate extensive experimental data and correctly assess the impact of these parameters to enable the quantitative prediction of cladding burst criteria in a realistic SFP-LOCA event.

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