Post-Test Analyses of the CMMR-4 Test

Understanding the final distribution of core materials and their characteristics is important for decommissioning the Fukushima Daiichi Nuclear Power Station (1F). Such characteristics depend on the accident progression in each unit. However, boiling water reactor (BWR) accident progression involves great uncertainty. This uncertainty, which was clarified by MAAP-MELCOR crosswalk, cannot be resolved with existing knowledge and was thus addressed in this work through core material melting and relocation (CMMR) tests. For the test bundle, ZrO2 pellets were installed instead of UO2 pellets. A plasma heating system was used for the tests. In the CMMR-4 test, useful information was obtained on the core state just before slumping. The presence of macroscopic gas permeability of the core approaching ceramic fuel melting was confirmed, and the fuel columns remained standing, suggesting that the collapse of fuel columns, which is likely in the reactor condition, would not allow effective relocation of the hottest fuel away from the bottom of the core. This information will help us comprehend core degradation in boiling water reactors, similar to those in 1F. In addition, useful information on abrasive water suspension jet (AWSJ) cutting for debris-containing boride was obtained in the process of dismantling the test bundle. When the mixing debris that contains oxide, metal, and boride material is cut, AWSJ may be repelled by the boride in the debris, which may cut unexpected parts, thus generating a large amount of waste in cutting the boride part in the targeted debris. This information will help the decommissioning of 1F.

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1 Introduction

Core degradation in a boiling water reactor (BWR) like the Fukushima Daiichi Nuclear Power Station (1F) has not been comprehensively understood. Since the reactor number 2 of Three Mile Island (TMI-2) accident, many studies have focused on the initial core melting and aspects related to the rupture of the pressure vessel in a pressurized water reactor (PWR). However, a few studies were conducted on reactor-core material relocation (CMR) from the core to the lower plenum. Particularly, a few studies analyzed BWR conditions with control rods and complicated core support structure in this relocation path. Core damage, melting, and slumping in the 1F accident may be different from those in the reactor number 2 of Three Mile Island nuclear generating station (TMI-2) accident because of the difference in structure between a BWR and a PWR.

The XR2-1 test [1,2], CORA test [3,4], and Phébus FP test series [4–6] can be cited as representative studies that simulate the core damage in a BWR system. Most of these tests simulated the behavior within the core region, and only the XR2-1 test, CORA-17 test [7], and CORA-28 test [8] focused on the relocation of material to the lower plenum. These tests confirmed that initial core damage in a BWR system was caused by eutectic melting due to contact between the control blade and channel box. The behavior in the bypass flow channel—that is, the space outside the channel box comprising the control blade, characterized the BWR system. In the XR2-1 test, downward flow of molten metals via a bypass was observed. However, even in this test, the temperature was limited basically to the melting point of relocating molten metal, and uncertainty remained about the CMR behavior in the high-temperature domain near the ceramic-fuel melting.

The uncertainty in the accident progression of a BWR is symbolically represented in Fig. 1. The actual scenario depends on phenomenological uncertainties related to the BWR-design condition in addition to the effect of boundary conditions, such as water level and pressure. The gas permeability of a high-temperature degraded core approaching the fuel melting and the downward relocation of hot core materials before fuel melting through the bypass and their effect on structure heating are important phenomena of the bifurcation point in accordance scenarios. Gas permeability contributes to delayed fuel melting to some extent under continuous vapor flow is continuously available. More importantly, relocation of high-temperature core material before fuel melting will play an important role in this bifurcation point. If the hottest part of the fuel relocates through the bypass down to the core support structure, then the peak core temperature can be effectively lowered, and support structure heating will be enhanced. This effective fuel relocation through bypass will have a tendency to lead to a continuous drainage path. If such BWR-specific fuel relocation does not occur, then its tendency to lead to a TMI-like path will increase. In a TMI-2 scenario, the core fuel melts and forms a molten pool surrounded by frozen fuel crust. When a molten pool is formed, the core support plate will experience little damage and the time of slumping will be delayed because liquid fuel can relocate through relatively narrow openings in the core-support-structure region. By contrast, in the drainage scenario where the hottest solid fuel relocates effectively down to the core-support-structure region, a molten fuel pool is not formed, and core materials will slump into the lower plenum, thereby creating a relatively large opening in the support structure region. An analysis of accident progression behavior by using severe accident (SA) codes MAAP5 and MELCOR was conducted by the Electric Power Research Institute (EPRI) [9]. The MAAP5 analysis supports the TMI-2 scenario, and the MELCOR analysis supports the drainage scenario.

In this study, core-material melting and relocation (CMMR) tests were performed to provide information to answer questions related to BWR design conditions; findings will improve the understanding of accident progression behavior in 1F plants [10–12]. As the reference for these test conditions, the assumed core condition before the slumping in Unit 2 of 1F (1F2) was adopted. Four tests (CMMR-1, CMMR-2, CMMR-3, and CMMR-4) were conducted using a small-scale test bundle. This study reported the results of the CMMR-4 test. On the basis of the test results, the accident progression in 1F2 was estimated and proposed as an improvement in the severe accident codes (MAAP5,
Concurrently, useful information for decommissioning obtained by dismantling the test bundle was gained and described.

2 Core-Material Melting and Relocation Test Design

The CMMR test equipment mainly comprised the test reactor, plasma heating system, and test bundle. A schematic of the CMMR test equipment is shown in Fig. 2. Each part is described in Secs. 2.1–2.3. In 2016, the CMMR-1 and CMMR-2 tests were conducted with this equipment to understand BWR core degradation [10]. In 2017, the CMMR-3 and CMMR-4 tests [11,12] were conducted with a larger test bundle compared with that used in the CMMR-1 and CMMR-2 tests.

2.1 Test Reactor. The test reactor was designed to simulate the melting of a fuel assembly by using a plasma heating system. The basic boundary of the test reactor vessel was an outer steel shell, which contained layers of insulating materials comprising combinations of refractory materials, such as alumina castable, ceramic zirconia, fibrous zirconia, and zirconia felt. The test reactor had a removable cover for making the access to the test bundle easier. The reactor cover had several discharges or off-gas ports for the argon gas supplied by the plasma heating system. The reactor cover had an optical access port to allow video recording of the melting dynamics by using a charge-coupled device (CCD) camera. A torch housing with a spherical ball gimbal and seal penetrated the reactor cover.

2.2 Heating System. The plasma heating system used for this program was a Phoenix Solutions Company (PSC) commercial-grade nontransferred torch (model PT200). The plasma heating

| Table 1 Properties of ZrO₂ the pellets |
|----------------------------------------|
| Chemical content | ZrO₂ | 97 wt % |
| MgO | 3 wt % |
| Physical properties | Melting temperature | Approximately 2500 °C |
| Density | 5.8 g/cm³ |

Fig. 1 Uncertainty in the accident progression of BWRs

Fig. 2 The CMMR test equipment

Fig. 3 Simulated part of a BWR fuel assembly
system comprised an arc starter system, argon supply, and closed-loop water-cooling heat exchange system for the torch. The plasma power supply provided up to 300 kW to the torch, and the output power was 200 kW. A small-scale test confirmed that the system can melt an oxide material [10].

2.3 Test Bundle. The targets prepared for this program were four test bundles (CMMR-1, CMMR-2, CMMR-3, and CMMR-4) that simulated a fuel rod bundle within a channel of the BWR. In this program, ZrO₂ pellets were installed instead of UO₂ pellets because ZrO₂ and UO₂ have both similar heat capacities and phase diagrams (Zr–UO₂ [13] Zr–ZrO₂ [14]). Moreover, CORA [3,4] and QUENCH [4,15] showed that both ZrO₂ and UO₂ have similar behaviors under a high temperature regime. The properties of the ZrO₂ pellets used for this program are shown in Table 1. The ZrO₂ pellets contained 3 wt% of MgO as a stabilizing binder and had a melting temperature of approximately 2500°C.

The test bundle that simulates a part of the BWR fuel assembly is shown in Fig. 3. The test bundle for the CMMR test was used to observe the melting dynamics of the control blade and channel box within an installation that simulates the lower support structure of the BWR core. In the CMMR-1, CMMR-2, and CMMR-3 tests, the control blade and channel box were placed at the center of the test bundles. Melting the ZrO₂ pellets on a massive scale was difficult because the control blade and channel box were placed at the center where plasma heating is the highest. Thus, the control blade and channel box were melted at an early stage, and a path for high-temperature gas was formed. Maintaining the upper part of the test bundle at a temperature that is sufficiently high to melt the ZrO₂ pellets was difficult. From this experience, the CMMR-4 test bundle was improved. Shifting the control blade and channel box from the center of the test bundle where the plasma heating has the highest temperature enabled the ZrO₂ pellets to be heated more intensively. Furthermore, in the CMMR-1, CMMR-2, and CMMR-3 test bundles, a relocation piece was installed to observe material relocation. However, in the CMMR-4 test, the relocation piece was not installed to prioritize melting of the ZrO₂ pellets on a massive scale.

Zircaloy-cladding tubes (48 rods) with a length of 800 mm contain 10 mm long ZrO₂ pellets. The Zircaloy-cladding tubes are integrated in a control blade assembly, which also simulates aspects of the tube bundle channel assembly. The top of the tube assembly is open. The tubes are open ended at the top and fixed at the bottom to the support plate of the lower structure. The control blade contains B₄C powder placed in stainless-steel tubes within a stainless-steel outer containment shell. The channel box and cladding tubes are made of zirconium alloys, such as Zircadyn 702.

Thermocouples (type C [W5%Re/W26%Re], capable of measuring up to 2330°C, accuracy in the temperature range 427–2315°C is ±1.00%) and an oxygen sensor, were installed in the test bundle to observe the temperature development and the
2.4 Test Conditions. The predicted accident progression in 1F2 is shown in Fig. 5. No core damage was expected when a safety relief valve was opened to depressurize the reactor at 18:02 on Mar. 14. After the depressurization of the reactor pressure vessel (RPV), the core started to heat up because the water level dropped below the core region due to flashing. As liquid water was lost from the core region, the core region was filled with water vapor and hydrogen that was generated mainly by Zr oxidation. Although water injection started at around 20:00 by using the fire engines, it was insufficient to reflood the core. In the BSAF Phase 2, a detailed study of the so-called three-peak period from around 19:30 on Mar. 14 to 1:30 on Mar. 15 was conducted. The study indicates a consensus that core degradation started just before the first of three pressure peaks and continued during the period where the RPV shows three very clear pressure peaks [16]. A large discharge of debris into the lower plenum is assumed at the second pressure peak at around 22:40 on Mar. 14, which is the target condition of the experiment.

The CMMR program aimed to examine the gas permeability of degraded fuel assemblies, melting/relocation of metals, and relocation of high-temperature fuel approaching its melting point, as well as heating of the structure. The test conditions are shown in Table 2. O₂ concentration in the test vessel (main gas is argon) was controlled at approximately 0.1% on the basis of Gibbs oxygen potential evaluation to simulate the steam-starved condition at 1F2. Figure 6 shows the axial temperature distribution of 1F2 analyzed by RELAP/SCDAPSIM. The lower part of the core remained cooled, and the temperature gradient of approximately 2500 °C/m was predicted [17]. With reference to the analysis results, the heating rate was set to determine the axial temperature distribution in the test. The following procedures were used for the CMMR-4 test:

| Core condition | Dry core |
|----------------|---------|
| Oxygen concentration | Around 0.1% (in Ar gas atmosphere) |
| Maximum temperature | Close to the melting point of ZrO₂ pellets (≈2500 °C) |
| Heating rate at the top (<1000 °C) | As quickly as possible |
| (>1000 °C) | 40 °C/min |

![Fig. 6 The axial temperature distribution of 1F2 analyzed by SCDAPSIM (reproduced from Ref. [17])](image)

![Fig. 7 Temperature histories of the CMMR-4 test](image)

![Fig. 8 Upper part of the test bundle during heating](image)
(1) The furnace was purged to reduce the O₂ concentration (<0.1%).
(2) The heating system (plasma torch) was started, and the upper level temperature was monitored until 1000°C was achieved (as quickly as possible).
(3) When the measured temperature of thermocouple C2 reached approximately 500°C, the power of the plasma torch was increased stepwise to achieve a heating rate of 40°C/min with reference to the values of the thermocouple C2.
(4) The heating rate was maintained until the maximum power level of the torch was achieved. This condition was held until shutdown.

3 Test Results
The heating history of the test is shown in Fig. 7. The test bundle was heated 40°C/min after reaching a temperature of 500°C with reference to according values of the thermocouple C2.

Throughout the test, the test atmosphere was controlled to <0.1%. The test ran for 90 min, and the heating power was kept at its maximum value for the last 60 min. Thermocouple C1 broke at the maximum temperature of a type-C thermocouple (2330°C). However, because ZrO₂ pellets were melted, the top of the test bundle was assumed to have been heated to ≥2500°C (melting point of ZrO₂ pellets). Therefore, the axial temperature gradient at the end of the test was considered to be ≥2200°C/m.

The transient behavior of the test bundle was confirmed by CCD cameras in the upper part of the reactor. The upper part of the test bundle during heating is shown in Fig. 8. Fifteen minutes after the test began, the control blade started to melt due to the eutectic reaction of Fe/B₄C. The upper part of the control blade was completely melted at 21 min, except for the B₄C, which completely melted at 23 min. The channel box began to melt at approximately 23 min. The control blade and channel box disappeared in the upper part of the test bundle at 31 min. The upper part of ZrO₂ pellets melted between 31 and 39 min, and the molten pool of oxide material was formed.
4 Post-Test Analyses

After the test, the test bundle was cut and analyzed to understand the melting behavior. The analysis was conducted in the order of appearance, observation, X-ray computed tomography (CT), cutting by abrasive water suspension jet (AWSJ), and analysis by electron probe micro-analyzer (EPMA) and X-ray diffraction (XRD). The information obtained in each step is described in Secs. 4.1–4.4 in more detail.

4.1 Appearance Observation. After the test, a part of the crucible of the test bundle was removed to visually observe the internal state of the test bundle. The test bundle after heating is shown in Fig. 9. Pickup positions are shown with reference to the upper surface of the lower tie plate. The test bundle at the upper part was heated to the melting point of the ZrO₂ pellets. After heating, unmelted ZrO₂ pellets remained standing in the shape of columns, with a pool of melted ZrO₂ pellets forming at the top of these columns. Melts were found in the lower and middle parts of the test bundle in the axial range from +500 mm to +600 mm. The melts may have been solidified in the middle part of the test bundle without flowing to the bottom, because they were chilled by touching the crucible during heating. In the absence of this influence, metallic melts flow down to the bottom. Moreover, spacer grids (Zircaloy) were not installed in the test bundle; even if they were installed, the melted spacer grids would flow down to the bottom, similar to the test result.

4.2 X-Ray-Computed Tomography. The test was conducted at a facility of PSC, USA, and the analysis was conducted in Japan. The test bundle was filled with resin before transport to maintain its internal state. To determine the internal state of the test bundle that cannot be visually confirmed, CT was performed in the experimental fast reactor Joyo and postirradiation examination facilities of the Japan Atomic Energy Agency (JAEA). A description of the X-ray CT apparatus and test conditions are presented in Fig. 10 and Table 3, respectively. In the part of (+250 to +800 mm), the control blade, channel box, and most of the cladding tube were destroyed, and the simulated fuel rods were deformed. At ≤+250 mm, bridging of molten cladding was observed. At ≤+110 mm, a part of the control blade remained as such. The upper part of the melted control blade relocated along the channel box and then solidified. Selective draining paths were present near the control blade, and complete blockage in the horizontal cross section was not detected. The simulated fuel columns survived, although they were exposed to high-temperature near-melting of ZrO₂ pellets.

4.3 Abrasive Water Suspension Jet Cutting. Boride produced by melting the control rod blades was present inside the test bundle. Boride is a very hard material, with a micro-Vickers hardness of ~19 GPa [18], thereby posing a cutting problem even in 1F decommissioning work. The test bundle was cut by performing AWSJ cutting, which is one of the effective methods for cutting hard materials. A similar cutting machine is considered for use for

| Table 3  | CT conditions                                                                 |
|----------|-------------------------------------------------------------------------------|
| CT measuremnet method | Translate/rotate                                                                 |
| X-ray source | Maximum electron energy: 9 MeV Maximum power: 30 Gy/min                       |
| X-ray device   | Silicon semiconductor detector • Number of channels: 0.06 deg × 100 ch Tungsten collimator • Slit size: 0.1 (W) × 2 (H) × 230 mm³ (L) • Number of slits: 100 |
| Measuring time | Normal imaging: 20 min/cross section Fine imaging: 80 min/cross section |

| Table 4  | Cutting conditions                                                               |
|----------|----------------------------------------------------------------------------------|
| Atmosphere | Underwater at room temperature                                                  |
| Abrasive  | Garnet, 150–300 μm                                                             |
| Abrasive supply rate | 1.5 kg/min                                                                   |
| Maximum pressure | 230 MPa                                                                  |

Fig. 10 Cross sections of the test bundle
Fig. 11 Cutting position of the test bundle

Fig. 12 Expected cutting part of sample (b)
1F decommissioning work [19]. AWSJ is a cutting method that involves mixing high-pressure water and abrasive in the injector mixer and then injecting it [20], cutting conditions are shown in Table 4. The cutting position shown in Fig. 11 was obtained from the CT results to determine the state of:

(a) Simulated fuel melted part
(b) Mixing or melted part of simulated fuel and control rod blade
(c) Accumulation of the melt at the bottom

Cutting a solidified melt with a complex mixture of materials is difficult because AWSJ may cut at unexpected points if the material distribution of the solidified melt is unknown. AWSJ selectively penetrates in areas that are easy to cut and is repelled in areas that are difficult to cut. The cut part of (b) is shown in Fig. 12. As shown in Table 5, cutting was performed three times at the locations where boride was deposited, as a result of the analysis described later. In the first and second cuts, the boride was not cut and AWSJ repelled by the boride escaped upward. In the second cut, the vessel was punctured by AWSJ cutting in an unexpected direction. The cutting speed gradually decreased each time, and the sample shown in Fig. 13 was finally cut out from the test bundle the third time. In the third cutting, AWSJ was injected on the part where the boride was deposited. Only the third AWSJ cutting itself required 84 kg of abrasive and 750 L of water. Moreover, the injection nozzle of AWSJ was replaced twice by cutting three times. In both cases, where boride was excluded in the cutting parts of (a) and (c), cutting was performed without any problem. The sample after AWSJ cutting was processed using a diamond cutter and automatic rotary grinding machine. The processed sample had a surface roughness $R_a < 0.1 \mu m$ and dimensions of $W80/2C2D80/2C2H20 mm^3$. The processed samples are shown in Fig. 14.

### 4.4 Electron Probe Micro-Analyzer and X-Ray Diffraction Analyses

For samples (a) and (b), simulated fuel ($ZrO_2$--Mg), fuel cladding (zirconia), and control rod blades (stainless steel and $B_4C$) were embedded as reference samples. EPMA and XRD analyses of samples (a), (b), and (c) were performed. The target elements were Fe, Zr, B, and Mg, which are the main elements of the test bundle. Mg is included as a binder for the simulated fuel $ZrO_2$.

**Simulated Fuel Melting Part.** The EPMA and XRD analyses results of sample (a) are shown in Fig. 15, and the detected phases by XRD are summarized in Table 6. The same level of Zr and O as the reference sample of simulated fuel was confirmed by
Fig. 15  EPMA and XRD analysis results of the simulated fuel melted part

### Table 6  Phases detected by XRD

| (Sample)-No. | Zr | ZrO<sub>2</sub> | ZrFe<sub>2</sub> | FeZr<sub>3</sub> | ZrB<sub>2</sub> | ZrC | C<sub>0.09</sub>Fe<sub>1.91</sub> |
|--------------|----|----------------|-----------------|----------------|--------------|-----|-----------------|
| (a)-1        | X  | X              | X               |                |              |     |                 |
| (b)-1        | X  | X              |                 |                |              |     |                 |
| (b)-2        | X  | X              |                 |                |              |     |                 |
| (b)-3        | X  | X              |                 |                | X            | X   |                 |
| (b)-4        | X  | X              |                 | X              |              |     |                 |
| (b)-5        | X  | X              |                 | X              | X            |     |                 |
| (b)-6        | X  | X              |                 |                |              |     |                 |
| (b)-7        | X  | X              |                 |                |              |     |                 |
| (c)-1        | X  | X              |                 |                |              |     |                 |
| (c)-2        | X  | X              |                 |                | X            |     |                 |
| (c)-3        | X  | X              |                 |                | X            |     |                 |
| (c)-4        | X  | X              |                 |                | X            |     |                 |
| (c)-5        | X  | X              |                 |                | X            |     |                 |
| (c)-6        | X  | X              |                 |                | X            |     |                 |
| (c)-7        | X  | X              |                 |                | X            |     |                 |
EPMA mapping. The melt was identified as ZrO₂ via XRD. Hence, this part is where the simulated fuel melted. Overall, the same Mg level as the reference sample of the simulated fuel was not confirmed. The temperature of the upper part of the test bundle was probably exposed to a temperature higher than the evaporation temperature of Mg. Many cavities were found in the simulated fuel that solidified after melting, thereby indicating that the molten simulated fuel probably blocked the gap between the fuel rods in the process of the gravitational flow to the bottom. The control rod blade was present on the right side of the sample before melting. No distribution of B and Fe, which are the components of the control rod blades, was found; thus, the control rod blades on the upper part of the test bundle probably melted without involving the simulated fuel.

**Molten and Mixing Part of Simulated Fuel and Control Rod Blade.** The EPMA and XRD analysis results of sample (b) are shown in Fig. 16, and the detected phases by XRD are summarized in Table 6. Unmelted simulated fuel rods remained identified just below the oxide pool. Simulated fuel rods were unmelted, but
cladding tubes were mostly melted. Although blockage was observed just below the oxide pool formation, the molten cladding tube did not block the gap between simulated fuel rods in the section where the unmelted simulated fuel rods were found. The molten cladding tube was discharged vertically downward. The control rod blade, which was placed on the right side of the sample, melted and disappeared. Boride, which was identified as mainly ZrB$_2$ by XRD, was deposited on the simulated fuel rods adjacent to the control rod blade. Fe and B contained in the control rod blades were not distributed in the entire sample, thus making it probable that the control rod blade did not spread much in the horizontal direction when discharged out vertically downward. Therefore, boride may have been deposited only on the simulated fuel rods adjacent to the control rod blade. In the cross section just below the oxide pool, melts were discharged vertically downward and did not spread laterally so that the permeability was ensured.

The Vickers hardness test result of sample (a) is shown in Fig. 17. The test force was 2.0–4.9 N. The Vickers hardness range of the entire sample (b) was 6.5–16.5 GPa. The boride-deposited part described in Chap. 4.3 was not a particularly hard part of the sample, but it was difficult to cut. It is possible that not only hardness but also toughness was affected.

Accumulation of Melt at the Bottom. The EPMA and XRD analysis results of sample (c) are shown in Fig. 18, and the detected phases by XRD are summarized in Table 6. The simulated fuel rods and control rod blade remain unmelted. Boron on the control rod blade had been removed during the cutting process. The temperature at the bottom of the test bundle during the test was $<1200^\circ$C. Cladding tubes that melted in the upper part of the test bundle were discharged vertically downward and accumulated on the lower tie plate. In CMMR-1, CMMR-2, and CMMR-3 tests, structures below the lower tie plate were introduced [10,11], so melts were discharged below the lower tie plate. By contrast, because the CMMR-4 test does not simulate a structure below the lower tie plate, melts discharged from the upper part were accumulated on the lower tie plate. Zr was accumulated on the entire lower tie plate; this Zr originated from the cladding tube and the channel box. The XRD results of (C)-3 and (C)-4 show that the fuel cladding tube was discharged along the simulated
fuel rods and deposited on the lower tie plate. ZrFe$_2$ and FeZr$_3$ were formed from the components of the control rod blades and were detected at the points in contact with the control rod blades. ZrFe$_2$ and FeZr$_3$ were not detected except at the contact points of the control rod blades; thus, the control rod blades did not spread laterally and were discharged vertically downward. The CT results also show that the control rod blade melt did not spread laterally. Boride was detected in the upper part but not in the bottom part. In part (c)-7. $C_{0.09}Fe_{1.91}$ was detected by XRD, not from the control rod blades but from the wire that fixed the test bundle.

5 Discussion

The CMMR-4 test was conducted to comprehend a BWR’s gas permeability of degraded fuel assemblies, the downward penetration of hot unmelted core materials, and their contribution to the heating of the structure by applying an estimated 1F2 condition just before slumping. The following results were confirmed for the CMMR-4 test: (1) Melting and relocation of metals (control blade, channel box, and fuel cladding tube) were widely observed. (2) Basically, the test bundle compositions were discharged vertically downward. (3) Selective draining paths were found near the control blade. (4) A complete blockage in the horizontal cross section did not form. (5) The simulated fuel columns survived, although they were exposed to high temperatures near the melting. Boride was detected in the upper part but not in the bottom part. ZrFe$_2$ and FeZr$_3$ formed. (6) The simulated fuel columns survived, although they were exposed to high temperatures near the melting of ZrO$_2$ pellets. From these results, the following characteristics specific to the BWR design condition are/were highlighted:

(a) Macroscopic gas permeability of the core approaching ceramic-fuel melting was confirmed under the simulated 1F2 condition. This macroscopic permeability involves (i) selective formation of molten-metal draining paths that prevent macroscopic blockage and (ii) absence of solid fuel swelling or sticking together that reduces the hydraulic diameters of the flow channels.

(b) The hot core fuel remained as columns in these tests, suggesting a possible actual BWR scenario where the weight of the upper core part would result in coherent collapse of fuel columns rather than pellet-wise relocation. Thus, the hottest part of fuel will not relocate effectively down to the core support structure.

Points (a) and (b) could be used to better simulate the 1F2 condition in MAAP5 and MELCOR applications. The MELCOR model seems to be in accordance with point (a) while effective relocation in point (b) may be enhanced more than in reality. By contrast, the MAAP5 model could slightly underestimate heat transfer from hot fuel and gas with point (a). However, because fuel melting will be reached sooner or later without effective relocation, the result does not seem to depend on this point. Therefore, provided that no effective relocation is featured, both codes will be consistent with the outcome of this study.

After the test, the test bundle was dismantled to determine its internal state. The control rod blade contained boron, which was why the melt contained boride in the test bundle after the test. AWSJ can perform cutting without any problem if it is used on a single rod material of consisting of oxide, metal, and boride. However, when cutting the mixed debris that contained oxide, metal, and boride material, AWSJ was repelled by the boride part in the debris, thereby cutting an unexpected part. Moreover, repeated attempts to cut the target location generated a large amount of waste of garnet and water required for cutting. In the decommissioning of 1F, this piece of knowledge should be considered debris that contains boride originating from control rods. The debris formed by melting the core material is suspected to have accumulated in the reactor vessel and the pedestal floor [21,22], and may also contain boride. When AWSJ is used for dismantling, this should be done with care, considering unexpected cutting and preventing so a large amount of secondary waste.

6 Conclusions

The CMMR-4 test was conducted to comprehend CMR in a BWR, like the 1F2, and address questions related to CMR (Q1: What about the gas permeability of the high-temperature core? Q2: What about the downward relocation of hot unmelted fuel and its heating of the structure?). The results are summarized as follows:

(1) The macroscopic gas permeability of the heated up core until ceramic-fuel melting will be kept.
(2) The hot fuel tends to remain as columns; thus, effective fuel relocation that removes the hottest fuel from the middle of the core and effectively heats the support structure, is unlikely.

This information can be utilized for better simulation of BWR-specific accident progression behavior with SA models.

The following information was obtained by cutting the melt of the test bundle with AWSJ:

- When debris that contains oxides, metals, and boride is being cut, AWSJ may be repelled by the boride and cut unexpected parts.
- Cutting debris containing boride produces large amounts of secondary waste (garnet and water).
- Abrasive water suspension jet is an effective method for debris cutting; however, when it is used at 1F, care should be taken to prevent damage around the object to be cut and to prevent the generation of secondary waste. This information will help in the decommissioning of 1F.

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Nomenclature

| Acronym | Description |
|---------|-------------|
| AWSJ    | Abrasive water suspension jet |
| BWR     | Boiling water reactor |
| CCD     | Charge-coupled device |
| CMRR    | Core material melting and relocation |
| CMRR    | Reactor-core material relocation |
| CT      | Computed tomography |
| EPMA    | Electron probe micro-analyzer |
| EPR     | Electric Power Research Institute |
| JAEA    | Japan Atomic Energy Agency |
| PSC     | Phoenix Solutions Company |
| PWR     | Pressurized water reactor |
| RPV     | Reactor pressure vessel |
| SA      | Severe accident |
| TMI-2   | Reactor number 2 of Three Mile Island nuclear generating station |
| XRD     | X-ray diffraction |

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