The CMMR Program: BWR Core Degradation in the CMMR-4 test

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ABSTRACT

For decommissioning the Fukushima Dai-ichi nuclear power plant (1F), understanding the final distribution of core materials and their characteristics is important. These characteristics obviously depend on the accident progression in each of the units. However, a large uncertainty is present in BWR accident progression behavior. This uncertainty, which was clarified by the MAAP-MELCOR Crosswalk, cannot be resolved with existing experimental data and knowledge. Once coolant is lost from the BWR core for some time, the following scenario can be divided symbolically into “TMI-2 Like Path” (molten fuel pool formation and relocation) and “Continuous Drainage Path” (fuel relocation basically without melting). In addition to the precise boundary conditions such as water level and pressure, the actual scenario depends on uncertainties in BWR-specific core material relocation (CMR). Main uncertainties for this branching point are summarized as two questions: How is gas permeability of high-temperature degraded core approaching fuel melting? (Q1) How is downward relocation of hot core materials before fuel melting and its effect on structure heating? (Q2). To address these questions, the core-material melting and relocation (CMMR) experiments were conducted. For the test bundle, ZrO₂ pellets were installed instead of UO₂ pellets. The test bundle consisted of 48 simulated fuel rods (ZrO₂ pellets clad in Zr alloy), a control blade (B₄C particles contained in SS tube and sheath) sandwiched by two channel box (Zr alloy) walls and lower support structures (SS). The height of simulated fuel rods of the CMMR-4 test was 80 cm. The heating system used for this program was the plasma heating capable of melting oxide materials (ZrO₂ pellets). The top of the test bundle was heated at 40 °C/min. The axial temperature gradient at the end of the test was 2200 °C/m or more. X-ray computed tomography was used to analyze the overall material distribution in the test bundle after the test. In the CMMR-4 test, useful information on core state just before slumping was obtained. Presence of macroscopic gas permeability of the core approaching ceramic-fuel melting was confirmed (A1) and the fuel columns stayed standing suggesting that collapse of fuel columns, which is likely in the reactor condition, would not allow “effective relocation” of the hottest fuel away to the bottom of the core thereby limiting the core maximum temperature and significantly heating the support structures (A2). This information will help us to comprehend core degradation in BWRs like those in the 1F.

KEYWORDS

Fukushima Dai-ichi NPP, Core degradation, BWR, CMR, Severe accident
1. INTRODUCTION

Core degradation in a boiling water reactor (BWR) like the Fukushima Dai-ichi nuclear power plant (1F) has not been comprehensively understood. Since the 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. In particular, a few studies analyzed BWR conditions with control rods and a complicated core support structure in this relocation path. Due to the difference in structure between a BWR and a PWR, core damage, melting, and slumping in the 1F accident may be different from that in the TMI-2 accident.

As representative studies simulating the core damage in a BWR system, the XR2-1 test [1, 2], the CORA test [3-4], and the Phébus FTP test series [4-7] can be cited. Most of these tests simulated the behavior within the core region, and only the XR2-1 test, CORA-17 [8] and CORA-28 [9] 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 a contact between the control blade and the channel box. The behavior in the “bypass flow channel”, i.e., the space outside channel box comprising control blade, was characterized for 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 ceramic fuel melting.

The uncertainty in the accident progression of a BWR is symbolically represented in Figure 1. In addition to effect of boundary conditions such as water level and pressure, the actual scenario depends on phenomenological uncertainties related to the BWR design condition. The “gas permeability of high-temperature degraded core approaching 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 branch point in scenarios. The gas permeability contributes to delay fuel melting to some extent when 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, peak core temperature can effectively be lowered and support structure heating will be enhanced. This effective fuel relocation through bypass will provide a tendency leading to “Continuous Drainage Path”. If such BWR-specific fuel relocation is not effective, its tendency leading to “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, since liquid fuel can relocate through relatively narrow openings in the core-support-structure region, little damage to the core support plate and the time of slumping will be delayed. In contrast, in the drainage scenario where hottest solid fuel relocates effectively down to the core-support-structure region, molten fuel pool is not formed and core materials will slump into lower plenum creating relatively large opening in the support structure region. An analysis of accident-progression behavior using the severe accident codes MAAP5 and MELCOR was conducted by the Electric Power Research Institute [10]. MAAP5 supports the TMI-2 scenario and MELCOR supports the drainage scenario.

In this study, a core-material melting and relocation (CMMR) experiments were performed to provide information to answer those questions related to BWR-design conditions so that understanding on accident progression behavior in 1F plants can be improved. As the reference for these test conditions, the assumed core condition before the slumping in Unit 2 of 1F (1F2) was adopted. Three tests (CMMR-1, -2, -3 and -4) were conducted using a small-scale test bundle. In this paper, results of the CMMR-4 test are reported. Based on the results of this program, we estimated the accident progression in 1F2 and proposed an improvement in the severe accident code.
Figure 1. The uncertainty in the accident progression of a BWR

2. CMMR EXPERIMENT DESIGN

The CMMR test equipment mainly comprised the test reactor, the plasma heating system, and the simulated fuel assembly. A schematic of the CMMR test equipment is shown in Figure 2. Each of these parts is described in the following section. In 2016, The CMMR-1 and -2 tests were conducted with the CMMR test equipment to understand BWR core degradation [11-12]. In 2017, the CMMR-3 and CMMR-4 tests were conducted with a larger test bundle compared with those in the CMMR-1 and -2 tests.

Figure 2. CMMR test equipment
2.1. Test Reactor

The test reactor was designed to simulate the melting of a fuel assembly using a plasma heating system. The basic boundary of the test reactor vessel was an outer steel shell. The shell 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 ease of access to the simulated fuel assembly. The reactor cover had several discharge or off-gas ports for the Ar gas that is supplied from the plasma heating system. The reactor cover had an optical access port to allow video recording of the melting dynamics using a charge coupled device (CCD) camera. A torch housing with a spherical ball gimbal and seal penetrated the reactor cover.

2.2. Plasma Heating System

The plasma heating system used for this program was a Phoenix Solutions Company commercial-grade non-transferred torch (model PT200). The plasma heating system comprised an arc starter system, an argon supply system, and a 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 test confirmed that it can melt an oxide material [11-12].

2.3. Simulated Fuel Assembly

The melting targets prepared for this program were four test bundles (CMMR-1, -2, -3 and -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 similar heat capacities and phase diagrams (Zr–UO₂ [13] and Zr–ZrO₂ [14]). In addition, CORA [3-4] and QUENCH [4, 15] showed that, under a high temperature, ZrO₂ and UO₂ have similar behaviors. The properties of the ZrO₂ pellets used for this program are shown in Table I. The ZrO₂ pellets contained 3wt% of MgO as a stabilizing binder and they had a melting temperature of approximately 2500 °C.

The test bundle simulate a part of a BWR fuel assembly is shown in Figure 3. The simulated fuel assembly for the CMMR test was used to observe the melting dynamics of the control blade and the channel box within an installation simulating the lower support structure of the BWR core. In CMMR-1, -2 and -3 tests, the control blade and the channel box were placed at the center of the test bundles. It was difficult to melt the ZrO₂ pellets on a massive scale. The reason is that the control blade and the channel box are placed at the center where the plasma heating is the highest, so that the control blade and the channel box melt at an early stage and a path for high temperature gas was formed. It was difficult to keep the upper part of the test bundle at a high temperature enough to melt the ZrO₂ pellets. From this experience, the test bundle of CMMR-4 has been improved. By shifting the control blade and the channel box from the center of the test bundle where the plasma heating is the highest temperature, the ZrO₂ pellets are more intensively heated. Furthermore, the test bundles of the CMMR-1, 2 and 3 tests are installed the relocation piece to observe materials relocation, but in the CMMR-4 test, the relocation piece is not installed to prioritize melting the ZrO₂ pellets on a massive scale.

The test bundle assembly are shown in Figures 4. Zircaloy-clad tubes (48 rods) with a length of 800 mm contain 10 mm-long ZrO₂ pellets. The zircaloy-cladding tubes are integrated with 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 a 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 the cladding tubes are made of zirconium alloys such as Zircadyne 702.
To observe temperature and material melting behavior, thermocouples (type C (W5%Re/W26%Re), capable of measuring up to 2330 °C), and an oxygen sensor were installed in the simulated fuel assembly. The location of each measuring instrument is shown in Figure 5.

Table I. Properties of ZrO₂ pellets

<table>
<thead>
<tr>
<th>Chemical content</th>
<th>ZrO₂</th>
<th>97 wt%</th>
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<tbody>
<tr>
<td>MgO</td>
<td></td>
<td>3 wt%</td>
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</table>

<table>
<thead>
<tr>
<th>Physical properties</th>
<th>Melting temperature</th>
<th>Approximately 2500 °C</th>
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<tbody>
<tr>
<td>Density</td>
<td></td>
<td>5.8 g/cm³</td>
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</table>

Figure 3. The simulated part of a BWR fuel assembly

Figure 4. Detailed assembly of a test bundle and overall features of the test hardware
2.4. Test Conditions

The predicted accident progression in 1F2 is shown in Figure 5. No core damage is expected when a safety relief valve was opened to depressurize the reactor. After that point, the core started to heat up because the water level dropped below the core region due to a flashing. As liquid water was lost from the core region, the core region filled with water vapor and hydrogen that was generated mainly by the oxidation of Zr. With the intention to simulate steam starved 1F2 condition, based on an oxygen potential evaluation, O\textsubscript{2} concentration in the test vessel (main gas is Ar) was controlled at around 0.1%. Under these circumstances, the core fuel could have reached its melting temperature and relocated. An accurate temperature history of the core up to degradation is not available.

The purpose of the CMMR program is to examine the gas permeability of degraded fuel assemblies, melting/relocation of metals and relocation of high-temperature fuel approaching melting point and their heating of the structure. The test conditions are shown in Table II. The axial temperature distribution of 1F2 analyzed by SCDAPSIM is shown in Figure 6. An analysis result that the high temperature axial gradient exists in the lower part of core region has been obtained. With reference to results of this analysis, the heating rate was set in order to realize the axial temperature distribution in the test.

The following procedures were used for the CMMR-4 test:
1. Purge the furnace to reduce the O\textsubscript{2} concentration (<0.1%).
2. Start the heating system (the plasma torch) and monitor the upper-level temperature until 1000 °C is achieved (as quickly as possible).
3. When the measured temperature of the thermocouple C2 reaches approximately 500 °C, the power of the plasma torch is stepwise increased to achieve a heating rate of 40 °C/min with reference to the thermocouple C2.
4. The heating rate is maintained until the maximum power level of the torch is achieved, at which point the condition is held until shutdown.

Table II. Test conditions

<table>
<thead>
<tr>
<th>Core condition</th>
<th>Dry core</th>
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<tr>
<td>Oxygen concentration</td>
<td>Around 0.1% (in Ar gas atmosphere)</td>
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<tr>
<td>Maximum temperature</td>
<td>Close to the melting point ZrO\textsubscript{2} pellets (≈2500 °C)</td>
</tr>
<tr>
<td>Heating rate at the top (&lt;1000 °C)</td>
<td>As quickly as possible</td>
</tr>
<tr>
<td>(&gt;1000 °C)</td>
<td>40 °C/min</td>
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</table>

Figure 5. 1F2 accident progression
3. TEST RESULTS

The CMMR-4 test was conducted in the test facility at Phoenix Solutions Company in 2018. There were no problems or malfunctions that were serious enough to compromise the validity of the test results.

3.1. Conduct of Test

The heating history of the test is shown in Figure 7. The simulated fuel assembly was heated at 40 °C/min after reaching a temperature of 500 °C with reference to the thermocouple C2. Throughout the test, the test atmosphere was controlled to less than 0.1%. The test ran for 90 min, and the heating power was kept at its maximum value for the last 60 min. The thermocouple C1 broke at the maximum temperature of a type C thermocouple (2330 °C). However, since ZrO₂ pellets were melted, it is assumed that the top of the simulated fuel assembly was heated to 2500 °C (the melting point ZrO₂ pellets) or more. Therefore, it is considered that the axial temperature gradient at the end of the test was 2200 °C/m or more.

The transient behavior of the simulated fuel assembly was confirmed by CCD cameras in the upper part of the reactor. The upper part of the simulated fuel assembly during the heating is shown in Figure 8. After 15 min into the test, 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 ≈23 min. The control blade and the channel box disappeared in the upper part of the simulated fuel assembly at 31 min. The upper part of ZrO₂ pellets melted between 31 min and 39 min, the molten pool of oxide material was formed.
Figure 7. Heating history of the CMMR-4 test

Figure 8. The upper part of the simulated fuel assembly during heating

3.2. Post-test condition

The simulated fuel assembly after heating is shown in Figure 9. Pickup positions are shown with reference to the upper surface of the lower tie plate. The simulated fuel assembly at the upper part was heated to the melting point of the ZrO$_2$ pellets. After the heating, unmelted ZrO$_2$ pellets remained standing in shape of columns, and the molten pool of melted ZrO$_2$ pellets was formed at the top of shape of columns. Metallic melt including Fe and Zr was found in lower and middle parts of the simulated fuel assembly. Concerning metallic melts including Fe and Zr in the range from +500 mm to +600 mm, it was considered...
that metallic melts solidified in the middle part of the simulated fuel assembly without flowing to the bottom, because metallic melts were chilled by touching the crucible during heating. In the absence of this influence, basically metallic melts flow down to the bottom. In additional, although the 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 like this test result.

The post-test condition of the test bundle was confirmed by X-ray computed tomography (CT) in the Experimental Fast Reactor Joyo and Post Irradiation Examination Facilities of the Japan Atomic Energy Agency. A description of the X-ray CT apparatus is shown in Table III.

Cross sections of the simulated fuel assembly by X-ray CT is shown in Figures 10. In the part of +250 to +800 mm, the control blade, the channel box, and most of the cladding tube were destroyed, and the simulated fuel rods were deformed. At +110 mm or less, a part of the control blade remained. The upper part of the melted control blade relocated along the channel box and then solidified. Relocating molten materials from the upper part of the simulated fuel assembly are accumulated in the lower tie plate.

<table>
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<th>Table III. Test conditions</th>
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<tr>
<td><strong>CT measurement method</strong></td>
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<tr>
<td>X-ray source</td>
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<td>X-ray device</td>
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<tr>
<td>Measuring time</td>
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Figure 9. Post-test appearance of the simulated fuel assembly
4. 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 heating of the structure applying estimated 1F2 condition just before slumping. The following results were confirmed for the CMMR-4 test. Melting and relocation of metals (the control blade, the channel box, and the cladding tube) were widely observed. There were selective draining paths near the control blade, and a complete blockage in the horizontal cross section was not formed. The simulated fuel columns survived, although they were exposed to high-temperature near the melting of ZrO₂ pellets.

From these results, following characteristics specific to the BWR design condition are highlighted:

(a) Macroscopic gas permeability of the core approaching ceramic-fuel melting was confirmed under the condition simulating the 1F2 condition. This macroscopic permeability consists of i) selective formation of molten-metal draining paths preventing macroscopic blockage, and ii) absence of solid fuel swelling or sticking together reducing flow channels.

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

Points (a) and (b) could be used for better simulation 1F2 condition in MAAP5 and MELCOR applications. The MELCOR model seems in accordance with the point (a), while “effective relocation” in the point (b) may be enhanced more than reality. The MAAP5 model on the other hand, may be slightly underestimating heat transfer from hot fuel and gas with the point (a). However, since fuel melting will be reached sooner or later if without “effective relocation”, thus the result does not seem much dependent on this point. Therefore, provided that no “effective relocation” is featured, both codes will be consistent with the knowledge from the present study.

5. CONCLUSIONS

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

(A1): The macroscopic gas permeability of the heated up core until ceramic fuel melting will be kept.

(A2): The hot fuel tends to remain as columns thus “effective fuel relocation” removing hottest fuel from the middle of the core and effectively heating the support structure is unlikely.

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

ACKNOWLEDGMENTS

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