Dry core degradation scenario and wet one in Fukushima Daiichi NPS core melt accident

TANABE Fumiya[1]

1. Sociotechnical Systems Safety Research Institute, 1140-4 Ichige, Hitachinaka-shi, Ibaraki 312-0033, Japan (tanabe@soctex.co.jp)

Abstract: In the Fukushima Daiichi Nuclear Power Station core melt accident, core degradation processes in the Unit 1 and Unit 3 would have proceeded along the wet core degradation scenario in which core damage and melt would have occurred in a condition that there was water within the active core to feed steam for zirconium-steam reaction. Then, large amount of hydrogen would have been generated by the reaction, which was enough for hydrogen explosion in the reactor building. Concerning core material relocation, metallic melt would have moved down and froze at or near the water/steam interface to form coherent crust above the core plate. On the crust, fuel material mixture of melt and solid would have accumulated. The fuel material mixture would have moved down into the lower plenum through two step relocation with the sequential abrupt failures of the crust and the core plate. The two distinguished steep pressure spikes observed in the Unit 3 reactor around 10:00 and 12:10 on 2011/3/13 can be interpreted with the two step fuel material relocation into the lower plenum. On the other hand, the core degradation process in the Unit 2 would have proceeded along the dry core degradation scenario in which core damage and melt would have occurred in a condition that there was no water within the core region above the core plate. The situation would have resulted in no steam generation in the core for zirconium-steam reaction. Then, there would not have been enough hydrogen for hydrogen explosion. It can interpret the fact that hydrogen explosion did not occur in the Unit 2. Concerning core material relocation, zirconium rich metallic melt would have gradually relocated into the lower plenum through existing coolant flow paths in the lower core structure. It can interpret the distinguished but gradual pressure increase observed in the Unit 2 reactor from 20:30 on 2011/3/14. Fuel material mixture of melt and solid would have accumulated on the core plate and then moved down into the lower plenum with abrupt failure of the core plate. It can interpret the distinguished rapid pressure increase in the Unit 2 reactor around 22:40 on 2011/3/14.

Keyword: Fukushima accident, core melt, relocation into lower plenum, zirconium-steam reaction, hydrogen

1 Introduction

In a series of papers by the present author, the process of core melt accident of each reactor in the Fukushima Daiichi NPS was investigated based on simple model calculation and observed data investigation, in which major sequences as well as characteristics of each reactor have been revealed[1],[2][3]. Among them, implications of the unique dry core condition during the core degradation (core damage and meltdown) process in the Unit 2 reactor have been revealed[2]. The analyses suggested that in the Unit-1 and Unit 3 reactor there would have been liquid water in the lower part of the core when core degradation occurs, which resembles the situation of the Three Mile Island Unit 2 (TMI-2) reactor accident[4], but not in the Fukushima Daiichi Unit 2 reactor. The fact of no hydrogen explosion in the Unit 2 reactor building was interpreted as due to essentially no hydrogen generation by zirconium-steam reaction because of absolute steam starvation condition in the dry core condition. Furthermore the first two distinguished reactor pressure increases in the 3/14 evening were interpreted as due to relocation of zirconium melt and uranium dioxide (UO_2) melt, respectively, into the lower plenum. Metallic melt relocation in the BWR dry core condition had been experimentally investigated[5]. Terminologies and its' implications of the dry core degradation scenario and the wet core degradation scenario had been discussed[5][6]. In the present paper, the hypothesis is further developed with more detailed description of the core material behavior with reference to these preceding reports and newly released measurement data.

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2 Brief description of the simple model calculation

2.1 Model description[1][2]

Uniform power distribution, axial and radial, within the core is assumed for simplicity. Uniform temperature is assumed among core materials above the water level. Uniform temperature among core materials below the water level is also assumed almost at the saturation temperature. Heat transfer to steam above the water level is neglected, and then the heat generated is consumed only in steam generation below the water level and heating-up of core materials above the water level. In the case that the time-dependent core water level curve is not available from measurements or reactor system analysis, it can be obtained with a simple equation from the above mentioned assumption. The zirconium-steam reaction starts at temperature of fuel cladding and fuel assembly canister around 1200 K and proceeds at runaway rate above 1500 K. In the runaway reaction phase, steam starvation is a dominant factor to constrain the reaction rate. Therefore, a simple model is adopted for the zirconium-steam reaction that the reaction begins at 1500 K and all steam generated below the water level reacts with zirconium.

2.2 Model calculation results[2]

2.2.1 Unit-1

The top of the active core was assumed to begin exposed to steam at 16:50 on 2011/03/11. The calculated behavior of the water level is shown in Fig.1.

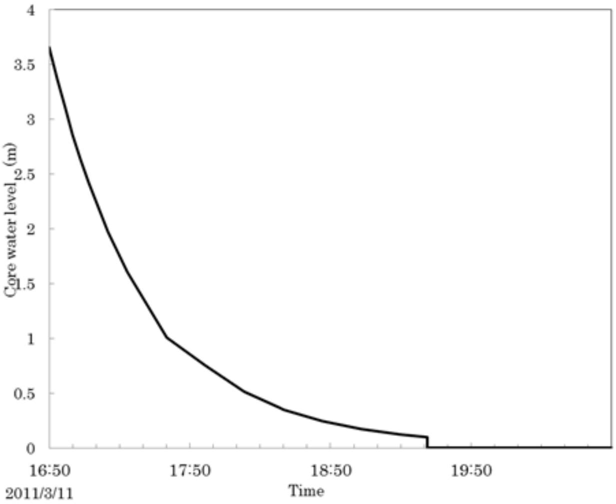

Fig.1 Core water level in the Unit 1 reactor calculated by the simple model.

The calculated result of the average temperature of the exposed core material is shown in Figure 2.

At 17:42 the average temperature of the exposed core material reaches 1200 K at which fuel rod cladding is expected to be ruptured due to inner pressure.

At 18:03 the temperature reaches 1500 K, when runaway zirconium-steam reaction starts on fuel rod cladding and channel box wall (fuel rod assembly canister), and it generates much heat and hydrogen.

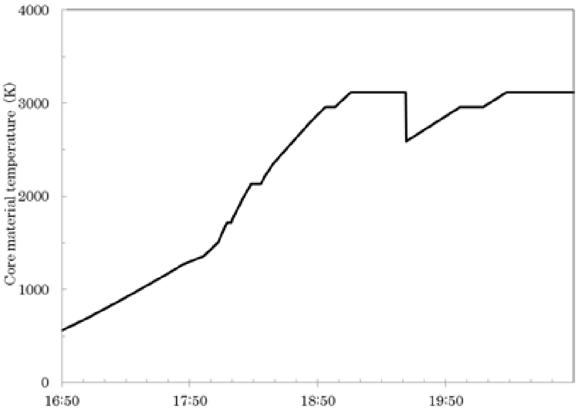

Fig.2 Exposed core material temperature in the Unit 1 reactor calculated by the simple model.

At 18:07 steel metal (Fe) of the control blade cladding begins melting at 1720K and terminates at 18:10.

At 18:18 Zircaloy metal (Zr) of fuel rod cladding and channel box wall starts melting at 2130 K and terminates at 18:23.

At 18:54 ceramic zirconium dioxide (ZrO_2) of the fuel rod cladding and channel box wall starts melting at 2960 K and terminates at 18:58.

At 19:05 ceramic uranium dioxide (UO_2) of fuel pellet starts melting at 3113 K and terminates at 19:31.

The accumulated mass of generated hydrogen is shown in Figure 3.

It is assumed for simplicity in the calculation that all of the exposed core material moves down together and interact with water at the termination of UO_2 melting (19:31). Then the water level is calculated to drop abruptly to zero at this time (Fig.1) and accumulated hydrogen mass is calculated to jump up to 453.5 kg at this time because all residual water in the core is assumed to react with high temperature zirconium relocating. It is expected in the actual course of the accident, on the contrary, that each metal and ceramic would have moved down on melting and froze with vaporizing water in the lower core. Therefore, the actual water level should have decrease faster than one in Fig.1 after Fe melting, and the actual accumulated hydrogen mass would have increased faster than the curve in Fig.3 with the same final value.

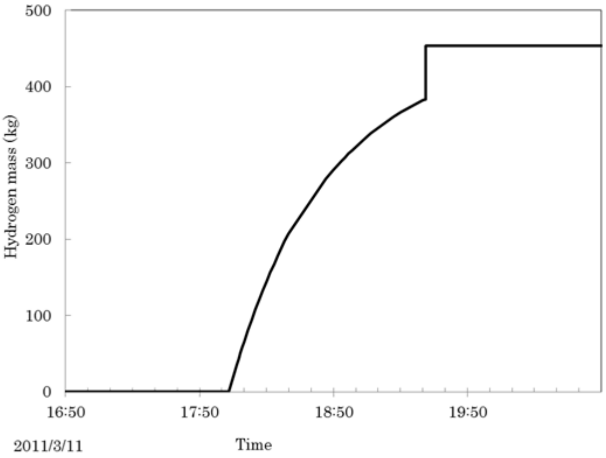

Fig.3 Accumulated hydrogen mass in the Unit 1 reactor calculated by the simple model.

2.2.2 Unit-3

The top of the active core was estimated to begin exposed to steam at 3:29 on 2013/03/11. The calculated behavior of the water level is shown in Fig.4.

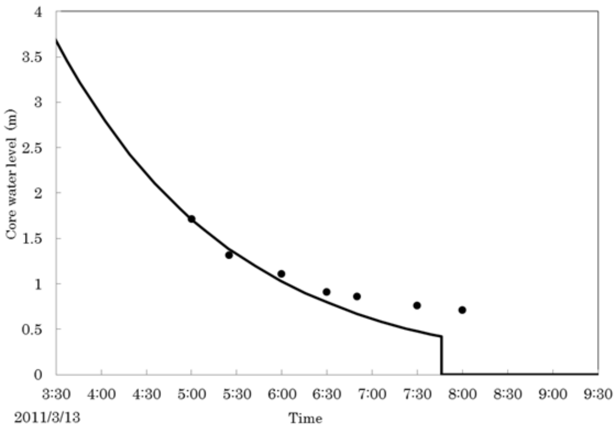

Fig.4 Core water level calculated in the Unit 3 reactor calculated by the simple model.

The calculated result of the average temperature of the exposed core material is shown in Figure 5. At 5:18 the average temperature of the exposed core material reaches 1200 K at which fuel rod cladding is expected to be ruptured due to inner pressure.

At 5:56 the temperature reaches 1500 K, when runaway zirconium-steam reaction starts on fuel rod cladding and channel box wall (fuel rod assembly canister), and it generates much heat and hydrogen.

At 6:02 steel metal (Fe) of the control blade cladding begins melting at 1720K and terminates at 6:04.

At 6:16 Zircaloy metal (Zr) of fuel rod cladding and channel box wall starts melting at 2130 K and terminates at 6:21.

At 6:57 ceramic zirconium dioxide (ZrO_2) of the fuel rod cladding and channel box wall starts melting at 2960 K and terminates at 7:06.

At 7:17 ceramic uranium dioxide (UO_2) of fuel pellet starts melting at 3113 K and terminates at 7:46.

The accumulated mass of generated hydrogen is shown in Figure 6.

It is assumed for simplicity in the calculation that all of the exposed core material moves down together and interact with water at the termination of UO_2 melting (7:46). Then the water level is calculated to drop abruptly to zero at this time (Fig.4) and accumulated hydrogen mass is calculated to jump up to 1210 kg at this time because all residual water in the core is assumed to react with high temperature zirconium relocating. It is expected in the actual course of the accident, on the contrary, that each metal and ceramic would have moved down on melting and froze with vaporizing water in the lower core. Therefore, the actual water level should have decrease faster than one in Fig.4 after Fe melting, and the actual accumulated hydrogen mass increase faster than the curve in Fig.6 with the same final value.

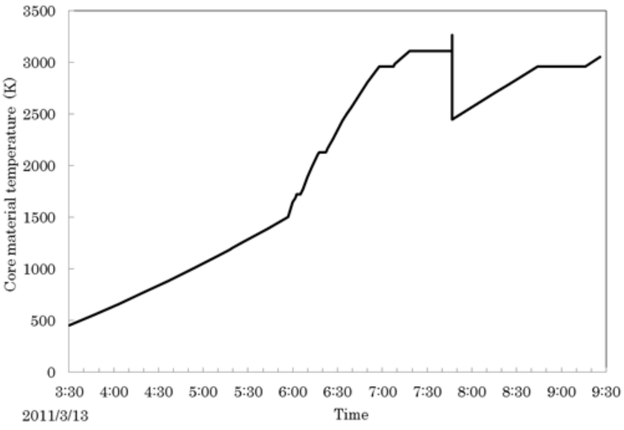

Fig.5 Exposed core material temperature in the Unit 3 reactor calculated by the simple model.

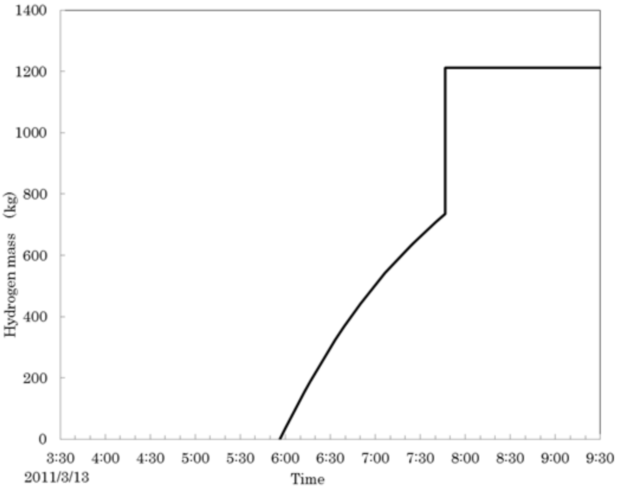

Fig.6 Accumulated hydrogen mass in the Unit 3 reactor calculated by the simple model.

2.2.3 Unit-2

From the measurement the top of the active core was estimated to begin exposed to steam at 16:20 on 2011/03/14 and the core water level decreases gradually as shown in Fig.7. And then the bottom of the core was estimated to get completely dry out at 18.22 due to depressurization flashing. The estimated water level is well below the bottom of the core plate (namely in the lower plenum). The water level was assumed below the core plate hereafter because it was highly probable that the sea water injected using the fire pump on fire engine had not reached the reactor vessel due to high reactor pressure even after initiation of the injection at 19:54.

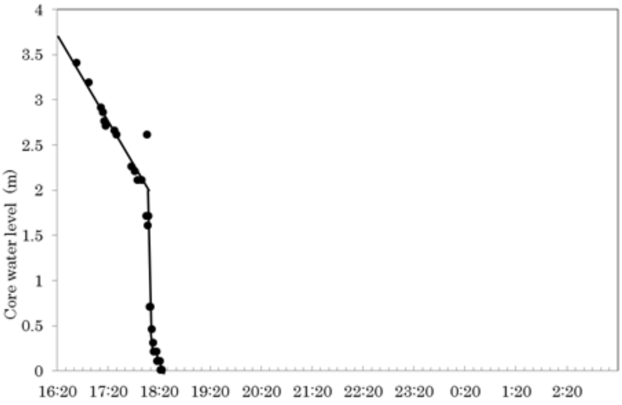

Fig.7 Core water level in the Unit 2 reactor interpolated with the measured values.

The core water level is shown in Figure 7, which is interpolation of the measured value.

The calculated result of the average temperature of the exposed core material is shown in Figure 8.

At 18:48 the average temperature of the exposed core material reaches 1200 K at which fuel rod cladding is expected to be ruptured due to inner pressure.

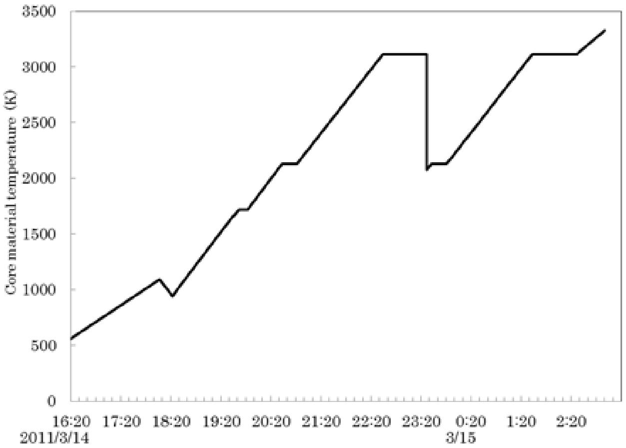

Fig.8 Exposed core material temperature in the Unit 2 reactor calculated by the simple model.

At 19:18 the temperature reaches 1500 K, when, if the water level was above the bottom of the active core, runaway zirconium-steam reaction should have started on fuel rod cladding and channel box wall (fuel rod assembly canister), and it should have generated much heat and hydrogen. Namely the completely dry core condition leads to no zirconium reaction because of absolute steam starvation.

At 19:42 steel metal (Fe) of the control blade cladding begins melting at 1720K and terminates at 19:51.

At 20:34 Zircaloy metal (Zr) of fuel rod cladding and channel box wall starts melting at 2130 K and terminates at 20:51.

At 22:34 ceramic uranium dioxide (UO_2) of fuel pellet starts melting at 3113 K and terminates at 23:27.

As matter of course, the accumulated mass of generated hydrogen is calculated to be zero kg.

3 Core degradation scenarios

Based on the simple model calculation results, a core degradation scenario is investigated for each reactor.

3.1 Wet core degradation scenario in the Unit 1

Based on the above described model calculation results, a hypothetical scenario is described for core degradation.

Around 16:50 the top of the active core begins exposed to steam and the core water level decreases hereafter.

Around 17:40 fuel rod cladding temperature reaches 1200 K to begin ruptured by overpressure.

Around 18:00, the temperature of the fuel rod cladding and channel box wall reaches 1500 K and then runaway zirconium-steam reaction starts to generate much heat and hydrogen. The control blade temperature reaches 1500 K and the control blade cladding and neutron absorber B_4C begins to form eutectic and the eutectic liquid moves down even when the temperature is much below the melting point of Fe (1720K) and B_4C(2700K). The moving-down liquid metal interacts with water in the lower core to freeze at or near the water liquid-steam interface (water level), and may form blockage between fuel channel box outer wall. Some liquid metal could move down to the bottom of the core on the core plate as fine particles. With increasing temperature, more eutectic liquid (Fe-B_4C) could accumulate over the blockage and attack the fuel channel box wall to form Fe/Zr eutectic (Fe rich eutectic) at around 1600 K. It could breach the channel box wall and some mixture metal liquid (Fe-Zr-B_4C) could move down inside of the fuel channel box.

At around 18:20, fuel rod cladding and channel box wall reaches melting points of zirconium (2130K), and zirconium liquid moves down to freeze at or near the water liquid-steam interface (water level), and may form blockage. Some zirconium metal liquid could move down to the bottom of the core on the core plate as fine particles. These blockage with frozen metal mixture (Zr-Fe-B_4C) could form continuous crust. The ceramic zirconium dioxide (ZrO_2) begins to melt at the melting point 2960K around 19:00, and ceramic uranium dioxide (UO_2) at the melting point 3113K around 19:10 and completed around 19:30. The mixture ceramic (ZrO_2-UO_2) melt move down and accumulate on the crust. However, it should be noticed that even below the melting point of UO_2, UO_2 could be dissolved into eutectic by Zr-melt and also UO_2 fuel pellets could fall down by mechanical interaction. Therefore, mixture of metallic melt (Zr-U), ceramic melt (ZrO_2-UO_2) and ceramic solid (ZrO_2-UO_2) would accumulate on the crust. The situation is very similar to the hypothesized core configuration of the Three Mile Island Unit 2 (TMI-2) reactor just before the restarting the reactor circulation pump RCP-2B at 174 minutes into the accident on March 28, 1979[4]. However, in the case of the TMI-2 at that time the crust is supposed to have been cooled by liquid water because of injected coolant water. In the case of the Unit-1 reactor core, water should have been vaporized by the heat from the fuel rods below the crust and the accumulated core material on the crust. Then the cooling of the crust should have been degraded and the crust would melt or fail. The core material collapses down on the core plate. It could be around 19:30. At this core material relocation on the core plate, the material would interact with the residual water above the core plate. It might generate steam to result in some abrupt pressure increase. It might not take so long time for the core plate failure with high temperature attack and large loading due to large amount of core material on it. Then, core material melt could abruptly drop into the lower plenum and generate large amount of steam with heat transfer to liquid water there. It results in steep pressure increase (pressure spike), which is the same mechanism as the hypothesized scenario in the TMI-2 accident between 224min and 226 min into the accident. There is no reactor pressure measurement in this time period in the Unit 1 because of station blackout, but it would have happened.

3.2 Wet core degradation scenario in the Unit 3

Based on the simple model calculation results, a hypothetical scenario is described for core degradation.

Around 3:30 on 2011/03/13 the top of the active core begins exposed to steam and the core water level decreases hereafter.

Around 5:20 fuel rod cladding temperature reaches 1200 K to begin ruptured by overpressure.

Around 6:00, the temperature of the fuel rod cladding and channel box wall reaches 1500 K and then runaway zirconium-steam reaction starts to generate much heat and hydrogen. The control blade temperature reaches 1500 K and the control blade cladding and neutron absorber B_4C begins to form eutectic and the eutectic liquid moves down even when the temperature is much below the melting point of Fe (1720K) and B_4C(2700K). The moving-down liquid metal interacts with water in the lower core to freeze at or near the water liquid-steam interface (water level), and may form blockage between fuel channel box outer wall. Some liquid metal could move down to the bottom of the core on the core plate as fine particles. With increasing temperature, more eutectic liquid (Fe-B_4C) could accumulate over the blockage and attack the fuel channel box wall to form Fe/Zr eutectic (Fe rich eutectic) at around 1600K. It could breach the channel box wall and some mixture metal liquid (Fe-Zr-B_4C) could move down inside of the fuel channel box.

At around 6:15, fuel rod cladding and channel box wall reaches melting points of zirconium (2130K), and zirconium liquid moves down to freeze at or near the water liquid-steam interface (water level), and may form blockage. Some zirconium metal liquid could move down to the bottom of the core on the core plate as fine particles. These blockage with frozen metal mixture (Zr-Fe-B_4C) could form continuous crust. The ceramic zirconium dioxide (ZrO_2) begins to melt at the melting point 2960K around 6:55, and ceramic uranium dioxide (UO_2) at the melting point 3113K around 7:15 and completed around 7:45. The mixture ceramic (ZrO_2-UO_2) melt move down and accumulate on the crust. However, it should be noticed that even below the melting point of UO_2, UO_2 could be dissolved into eutectic by Zr-melt and also UO_2 fuel pellets could fall down by mechanical interaction. Therefore, mixture of metallic melt (Zr-U), ceramic melt (ZrO_2-UO_2) and ceramic solid (ZrO_2-UO_2) would accumulate on the crust. As discussed in the Unit 1, the situation is very similar to the hypothesized core configuration of the TMI-2 reactor just before the restarting the reactor circulation pump RCP-2B at 174 minutes into the accident on March 28, 1979. Some time later, the crust would melted or fail. The core material collapses down on the core plate. At this core material relocation on the core plate, the material would interact with the residual water above the core plate. It might generate steam to result in some abrupt pressure increase. The first abrupt pressure spike in the observed reactor pressure in the Unit 3 as shown in the Fig.9 around 10:00 could be interpreted as due to this core material relocation onto the core plate due to the abrupt crust failure.

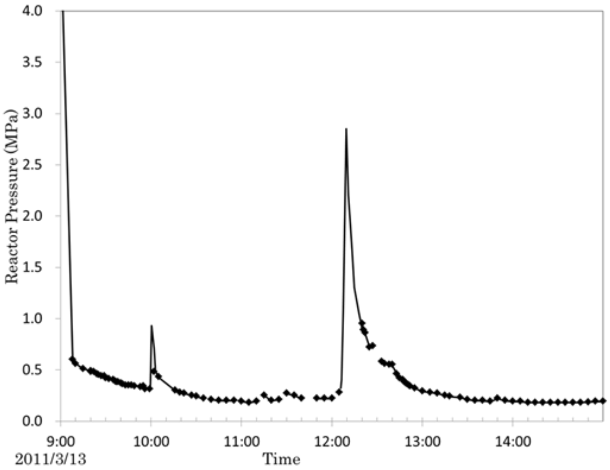

Fig.9 Measured reactor pressure in the Unit 3 (Digital data and analog chart record are integrated.).

It might not take so long time for the core plate failure with high temperature attack and large loading due to large amount of core material on it. Then, the mixture of core material melt and ceramic could abruptly drop into the lower plenum and generate large amount of steam with heat transfer to liquid water there. It would result in steep pressure increase (pressure spike), which is the same mechanism as the hypothesized scenario in the TMI-2 accident between 224min and 226 min into the accident. The second distinguished pressure spike in the reactor pressure in the Unit 3 as shown in Fig.9 around 12:10 could be interpreted as due to this abrupt core material relocation into the lower plenum due to the abrupt core plate failure.

3.3 Dry core degradation scenario in the Unit 2

Based on the simple model calculation results, a hypothetical scenario is described for core degradation.

Around 16:20 on 2011/03/14 the top of the active core begins exposed to steam and the core water level decreases gradually hereafter.

Around 18:50 fuel rod cladding temperature reaches 1200 K to begin ruptured by overpressure.

Around 19:20, The control blade temperature reaches 1500 K and the control blade cladding and neutron absorber B_4C begins to form eutectic and the eutectic liquid moves down even when the temperature is much below the melting point of iron (1720K) and B_4C(2700K). The moving-down liquid metal may freeze and form blockage between fuel channel box outer wall. However some liquid metal could reach the bottom of the core on the core plate to freeze. With increasing temperature and reaching the Fe melting point 1720 K, more metal liquid (Fe-B_4C) could accumulate over the blockage and attack the fuel channel box wall to form Fe/Zr eutectic (Fe rich eutectic) at around 1600 K. It could damage the channel box wall and some mixture metal liquid (Fe-Zr-B_4C) could move down inside of the fuel channel box and some could reach the bottom of the nose piece. At this stage, as observed in the XR2-1 BWR metallic melt relocation experiment[5], the melt could not have relocated down into the lower plenum. Around 20:34, temperature of fuel rod cladding and channel box wall reaches melting points of zirconium (2130 K), and zirconium metal liquid moves down and attack the accumulated frozen Fe-Zr-B_4C metal with eutectic interaction. The eutectic interaction would re-melt the frozen metal and make penetrations for the metal melt to relocate into the lower plenum as observed in the XR2-1 experiment[5]. In the above mentioned eutectic interaction, the fact that the eutectic liquidus temperatures for the Zr-Fe system can be as low as 1220 K for zirconium rich mixture would play a key role[5]. The relocation paths would be through the existing coolant flow paths, as suggested in the XR2-1report, such as through the fuel assembly nose piece and the inlet nozzle into the lower plenum, and through the control blade guide tubes over the control blade velocity limiter into the lower plenum[5].

Hereafter, the metal liquid (Zr-Fe-B_4C) would have continuously drained into the lower plenum and interacting with water there to generate steam. The first distinguished but gradual pressure increase from 20:30 on March 14 in the observed reactor pressure as shown Fig.10 can be interpreted as due to this gradual relocation of the mixture metal liquid into the lower plenum.

Around 22:35, with increasing temperature of the core material, the ceramic uranium dioxide (UO_2) begins to melt at the melting point 3113K and the melting gets completed around 23:27. The ceramic melt (UO_2) moves down and accumulates over the remaining frozen metal on the core plate. However, it should be noticed that even below the melting point of UO_2, UO_2 could be dissolved into eutectic by Zr-melt and also UO_2 fuel pellets could fall down by mechanical interaction. Therefore, mixture of metallic melt (Zr-U), ceramic (UO_2) melt and ceramic solid (UO_2) accumulate on the core plate. The core plate is heated by the molten mixture and stressed by the weight of the material, and finally abruptly gets failed. Then large amount of the very high temperature core material, most of which is fuel, would have fallen suddenly into the lower plenum. Then it interacts with water there and generates large amount of steam to result in abrupt reactor pressure increase. The second distinguished pressure peak increasing abruptly around 22:40 on March 14 in the observed reactor pressure (Fig.10) can be interpreted as due to this abrupt relocation of the fuel material (UO_2). In the pressure increase, the recorded value is 0.428MPa (gage) at 22:40 and 1.823MPa at 22:50. Therefore the pressure should have increased in a shorter time, probably within several minutes, which resembles to the pressure spikes in the Unit-3 and the TMI-2.

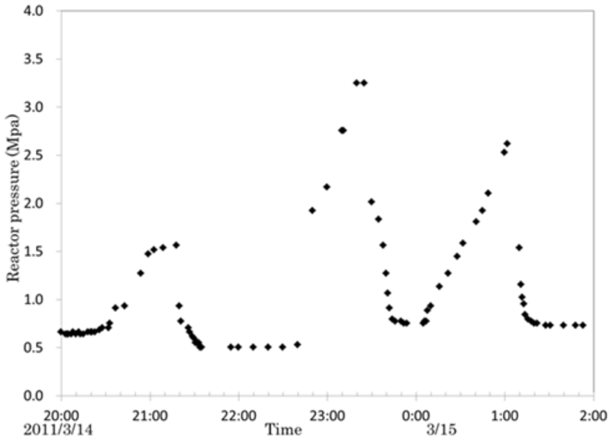

Fig.10 Measured reactor pressure in the Unit 2.

4 Discussions

4.1 Probability of the dry core condition in the Unit 2-Validity of the dry core assumption

In the preceding paper, the sea water through fire pumps on a fire engine was assumed unable to reach the reactor vessel from restarting the pump at 19:54 through 15th morning because of high pressure condition in the RPV. The hypothesis is further strengthened by the recent released findings. A fire pump on a fire engine had been initiated at around 15:30 on 2011/3/14 to start injecting sea water into the RPV soon after the RPV depressurization. But at 19:20 the fire truck was found to have been running out of fuel oil for 0.5-1.0 hour[7]. A recent newspaper article reports that the NPS manager received the report on the fire pump out of working at 18:28[8]. Therefore it is highly probable that sea water should not have been injected. The fire pump was restarted at 19:54. But it has recently been revealed that a large part of injected sea water should have bypassed into other facilities such as a condensate storage tank[7]. Therefore it is also highly probable that sea water should not have reached the RPV even from restarting the pump at 19:54 through 15th morning. Then dry core hypothesis is highly probable.

4.2 Zirconium-steam reaction in the dry core condition in the Unit 2

The simple model leads to no zirconium-steam reaction in the Unit 2 reactor core before core material relocation into the lower plenum because of no steam feed from water boiling in the core. Then the reason of the no hydrogen explosion in the Unit 2 is interpreted as due to little hydrogen generation. This interpretation is unique because other reports interpreted it as the blow-out panel failure in the Unit 2 reactor building due to the hydrogen explosion in the Unnt-1 reactor building.

In the first TEPCO's Unit 2 analysis using MAAP code, the total accumulated hydrogen generated is estimated about 360kg in the case 2[9]. In the case 2, the sea water injection rate is tuned in order to keep the water level just at the bottom of the active fuel (BAF) and obtain more reasonable result than the case 1 in comparison with the observed plant data. It should be noticed that in the case 2 there should be no steam generation in the core because of no water in the active fuel region. Then there is essentially no steam to react with zirconium. Then the reaction cannot proceed. Therefore the amount of hydrogen generated is not rational. It suggests that the TEPCO's MAAP analysis could not take account of the effect of steam starvation appropriately. JNES performed a cross check analysis for the TEPCO's first analysis using MECOR code[10]. The total accumulated hydrogen generated is estimated about 810 kg in the utility's analysis 2nd corresponding to TEPCO's case 2. In the JNES's analysis, the sea water injection rate is assumed unable to reach the RPV at RPV pressure higher than 0.6MPa, which results in little water injected and the water level kept below the core plate after the reactor depressurization around 18:00. As discussed on the TEPCO's case 2, it should be noticed that there should be no steam generation in the core because of no water in the active fuel region. Then there is essentially no steam to react with zirconium. Then the reaction cannot proceed. Therefore the amount of hydrogen generated is not rational. It suggests that the JNES's analysis also could not take account of the effect of steam starvation appropriately.

In the second analyses of TEPCO[11] and JNES[12], sea water injection rate are tuned in order to adjust the hydrogen generation rate fitting to the dry well pressure increase in the 3/14 evening. In the cases there is water in the core when core degradation occurs. Then the situation belongs to wet core degradation scenario. Although the calculations seem to reproduce the dry well pressure behavior, the calculated results on the core behavior are become far worse than the first analyses. Then the analyses seems wrong.

5 Conclusions

Core degradation process in each Fukushima Daiichi NPP Unit 1, Unit 2 and Unit 3 reactor is further hypothetically clarified. In the Unit 1 and Unit 3, core degradation would have proceeded along the wet core degradation scenario, which is defined as a scenario that there is liquid water within the active core region when core degradation occurs. Then steam would have feed to zirconium-water reaction generating large amount of hydrogen enough to result in hydrogen explosion in the reactor building which actually occurred. Core material relocation is supposed to proceed as follows: At first, molten metal (Fe, B_4C, Zr) would have flowed down and frozen at or near the water level to form a continuous crust. Mixture of relocating molten ceramic and solid ceramic (ZrO_2, UO_2) would have accumulated on the crust. The ceramic core material would have relocated abruptly onto the core plate with the metallic crust failure by melting or mechanical loading. Then some time later, the ceramic core material would have abruptly relocated into the lower plenum with the core plate failure by melting or mechanical loading. The above mentioned two steps abrupt relocating process into the lower plenum would have generated much steam resulting rapid pressure increases (pressure spikes). The distinguished pressure spikes in the measurement data of Unit 3 reactor (around 10:00 and 12:10) can be interpreted as due to this two steps relocation.

In the Unit 2, on the other hand, core degradation would have proceeded along the dry core degradation scenario, which is defined as a scenario that there is no liquid water in the core region above the core plate when core degradation occurs. Then there is no steam generation in the core to feed to zirconium-water reaction.

Even taking account of some steam generation in the lower plenum with heat transfer from the vessel wall and relocating core material, the amount of generated hydrogen would not have been enough to result in hydrogen explosion in the reactor building. It could be the reason of the fact that hydrogen explosion did not occurred in the Unit 2 reactor building. Core material relocation is supposed to proceed as follows: At first, molten metal (Fe, B_4C, Zr) would have flowed down and frozen on or above the core plate. Next, molten zirconium would have flowed down and attack the accumulated frozen Fe-Zr-B_4C metal with eutectic interaction and relocated into the lower plenum through existing coolant flow paths in the lower core structures. The paths are through the fuel assembly nose piece and the inlet nozzle into the lower plenum, and through the control blade guide tubes over the control blade velocity limiter into the lower plenum. The relocation process would have been rather gradual, and then it would have resulted in gradual reactor pressure increase. The distinguished but gradual pressure increase in the Unit-2 reactor starting from 20:30 on 3/14 2011 can be interpreted with this relocation. Finally mixture of metallic melt (Zr-U), ceramic (UO_2) melt and ceramic solid (UO_2) accumulate on the core plate. The core plate is heated by the molten mixture and stressed by the weight of the material, and finally abruptly gets failed. Then large amount of the very high temperature core material, most of which is fuel, would have fallen suddenly into the lower plenum. Then it interacts with water there and generates large amount of steam to result in abrupt reactor pressure increase. The second distinguished pressure peak increasing abruptly around 22:40 on March 14 in the observed reactor pressure can be interpreted as due to this abrupt relocation of the fuel material (UO_2).

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