Post-facta analyses of Fukushima accident

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Abstract: Independent analyses by the present author on Fukushima accident are introduced. The analyses have been performed of the core melt behavior of the Unit 1, Unit 2 and Unit 3 reactors of Fukushima Daiichi Nuclear Power Station on March 11th-15th, 2011. The analyses are based on a phenomenological methodology with measured data investigation and a simple physical model calculation. Estimated are time variation of core water level, core material temperature and hydrogen generation rate. The analyses have revealed characteristics of accident process of each reactor. In the case of Unit 2 reactor, the calculated result suggests little hydrogen generation because of no steam generation in the core for zirconium-steam reaction during fuel damage process. It could be the reason of no hydrogen explosion in the Unit 2 reactor building. Analyses have been performed also on the core material behavior in another chaotic period of March 19th-31th, 2011, and it resulted in a re-melt hypothesis that core material in each reactor should have melted again due to shortage of cooling water. The hypothesis is consistent with many observed features of radioactive materials dispersion into the environment. The analyses show validity and importance of independent analyses based on simple physical model calculation.

Keyword: Fukushima Daiichi accident; core melt; re-melt; simple physical model

1 Introduction

In a series of papers by the present author, the process of core melt accident of each reactor in the Tokyo Electric Power Company (TEPCO) Fukushima Daiichi NPS (1F) 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 Fukushima Daiichi Unit 2 (1F2) reactor have been revealed.[2] The analyses suggested that in the Fukushima Daiichi Unit-1 (1F1) and Unit 3 (1F3) 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 1F2 reactor. The fact of no hydrogen explosion in the 1F2 reactor building was interpreted as due to little hydrogen generation by zirconium- steam reaction because of extreme steam starvation condition in the dry core condition. Furthermore the two distinguished pressure increases in the 1F2 reactor pressure vessel (RPV) on March 14th evening were interpreted as due to relocation of zirconium melt and uranium dioxide (UO_2) melt, respectively, into the lower plenum. Based on the preceding research results on metallic melt relocation in the BWR dry core condition[5] and the dry or wet core degradation scenario[6] , the hypothesis is further developed with more detailed description of the core material behavior. The re-melt phase is also analyzed.

2 Analyses of the first core melt phase

2.1 Brief 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. In the runaway reaction phase of zirconium-steam reaction, 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

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1500 K and all steam generated below the water level reacts with zirconium.

2.2 Model calculation results [2]

Analysis results on the major events in each reactor are summarized in Table 1.

2.3 Core degradation scenario

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

2.3.1 Wet core degradation scenario in the Unit 1

Table 1 shows that core damage and core melt would have occurred in the Unit-1 in a condition that there was water within the active core, which corresponds to the wet core degradation scenario.

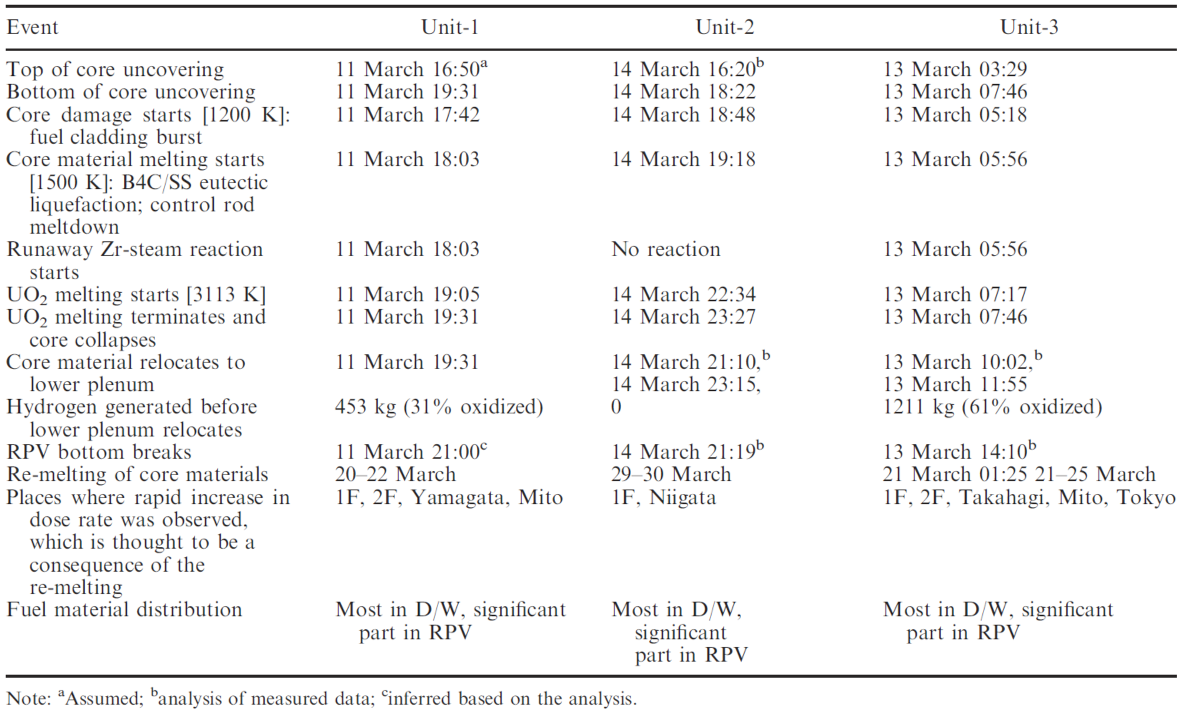
Based on the above described model calculation results, a hypothetical scenario is described for core degradation.

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 interact 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.

Table 1 Analysis results on major events in Fukushima Daiichi nuclear reactors[2]



Event	Unit-1	Unit-2	Unit-3
Top of core uncovering	11 March 16:50[a]	14 March 16:20[b]	13 March 03:29
Bottom of core uncovering	11 March 19:31	14 March 18:22	13 March 07:46
Core damage starts [1200 K]: fuel cladding burst	11 March 17:42	14 March 18:48	13 March 05:18
Core material melting starts [1500 K]: B4C/SS eutectic liquefaction; control rod meltdown	11 March 18:03	14 March 19:18	13 March 05:56
Runaway Zr-steam reaction starts	11 March 18:03	No reaction	13 March 05:56
UO_2 melting starts [3113 K]	11 March 19:05	14 March 22:34	13 March 07:17
UO_2 melting terminates and core collapses	11 March 19:31	14 March 23:27	13 March 07:46
Core material relocates to lower plenum	11 March 19:31	14 March 21:10,[b] 14 March 23:15,	13 March 10:02,[b] 13 March 11:55
Hydrogen generated before lower plenum relocates	453 kg (31% oxidized)	0	1211 kg (61% oxidized)
RPV bottom breaks	11 March 21:00[c]	14 March 21:19[b]	13 March 14:10[b]
Re-melting of core materials	20–22 March	29–30 March	21 March 01:25 21–25 March
Places where rapid increase in dose rate was observed, which is thought to be a consequence of the re-melting	1F, 2F, Yamagata, Mito	1F, Niigata	1F, 2F, Takahagi, Mito, Tokyo
Fuel material distribution	Most in D/W, significant part in RPV	Most in D/W, significant part in RPV	Most in D/W, significant part in RPV

Note: [a]Assumed; [b]analysis of measured data; [c]inferred based on the analysis.

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 blockages 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 28th, 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 1F1 reactor core, some 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 1F1 because of station blackout, but it would have happened.

2.3.2 Wet core degradation scenario in the Unit 3

Table 1 shows that core damage and core melt would have occurred in the Unit-3 in a condition that there was water within the active core, which corresponds to the wet core degradation scenario.

Based on the simple model calculation results, a hypothetical scenario for core degradation was developed. It is quite similar to the case of Unit-1, and then only the behavior after completion of melting of ceramic uranium dioxide (UO_2) around 7:45 on March 13th is described. Mixture of metallic melt (Zr-U), ceramic melt (ZrO_2-UO_2) and ceramic solid (ZrO_2-UO_2) would accumulate on the crust.

Short time later, the crust would melt 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 1F3 as shown in the Fig.1 around 10:00 could be interpreted as due to this core material relocation onto the core plate due to the abrupt crust failure.

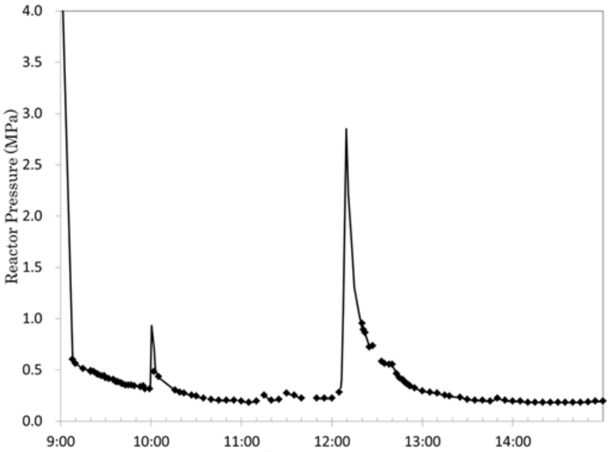


Fig.1 Measured reactor pressure in the Unit 3 (Digital data[7] and analog chart record[8] are integrated.).

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). The second distinguished pressure spike in the reactor pressure in the 1F3 as shown in Fig.1 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.

2.3.3 Dry core degradation scenario in the Unit 2

Table 1 suggests that core damage and core melt would have occurred in the Unit-2 in a condition that there was no water within the core region above the core plate, which corresponds to the dry core degradation scenario. Such a dry core condition would have been a consequence of large amount of water vaporization due to the RPV depressurization with opening a safety relief valve around 18:00 without successful water injection. Even after starting water injection at 19:54, water could not have reached the core due to the high pressure RPV condition and bypassing. High probability of the dry core hypothesis will be further discussed in detail in **4.1.**

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

Around 16:20 on March 14th, 2011 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 *Fe* (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 liquid 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 14th in the observed reactor pressure as shown in Fig.2 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 14th in the observed reactor pressure (Fig.2) 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 1F3 and the TMI-2.

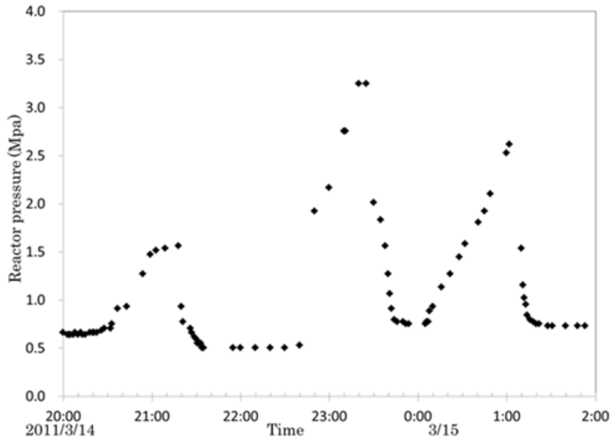


Fig.2 Measured reactor pressure in the Unit 2[7].

3 Analyses of re-melt phase

3.1 Analysis of the Unit 1 reactor

From 05:46 on March 12th, a large amount of water had been injected into the RPV of the Unit 1 reactor. It seemed as if the core materials had been essentially cooled down even with most having been once molten. However, a detailed investigation of the measured data considering energy balance revealed the actual situation. Injection water flow rate is shown in comparison with the minimum decay heat removal flow rate (MDHRFR) in Fig.3. MDHRFR is defined as the water flow rate which can compensate the water loss with vaporization due to decay heat of nuclear fuel when 100% of the decay heat is spent for water heating and vaporization. As shown in Fig.3, there are two periods in which injection flow rate is not enough for decay heat removal. The first one is on March 14th, which suggests that the core and lower plenum material melted again on March 14th. The second one is the period from March 20th through March 22nd, when the water injection rate is about 30% of the MDHRFR. Considering the high probability of some breaks at the reactor pressure vessel (RPV) bottom through which a considerable amount of water flows out without contributing to core material cooling, the effective water flow rate will have been less than 30% of the MDHRFR. The stored energy in the core materials increases with shortage of cooling.

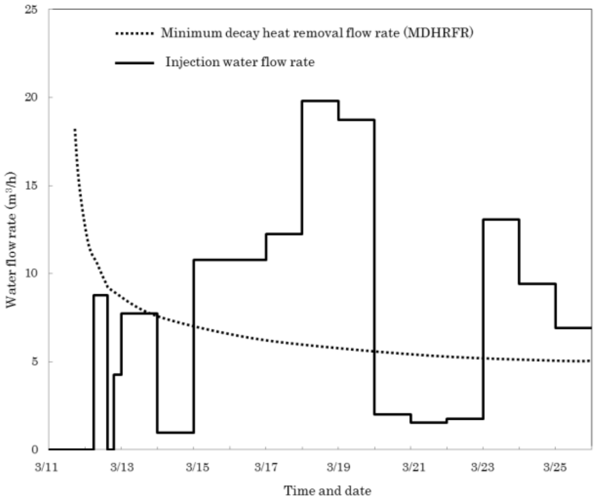


Fig.3 Injection water flow rate in comparison with MDHRFR in the Unit 1.

The additional stored energy within only one and a half days is enough to result in melting of all materials in the core and lower plenum. Considering the significant water flowing out/down through some breaks at the bottom of the lower plenum, additional stored energy is expected to increase faster than mentioned above. Furthermore, considering that the injection rate probably would have been reduced earlier than 00:00 March 20th, the re-melt could have started even on March 20th, and a large amount of radioactive materials would have been released to the environment. The very high temperature behavior at the RPV outside surface corresponds well to the above scenario. The peaks in the measured dose rate at the 1F site, a sharp peak at Fukushima Daini Nuclear Power Station (2F), a small peak in Mito City and a sharp increase in Yamagata City on March 20th and a peak in Niigata City on March 20th could be a consequence of this release. The air radioactivity concentration of *I-131*, which was measured in Chiba City by Japan Chemical Analysis Center (JCAC) and in Tsukuba City by High Energy Accelerator Research Organization (KEK). Some part of the peak on March 21st, which was sampled from March 20th 9:00 through March 21st 9:00, could have been contributed by this release on March 20th. The air radioactivity concentration ratio of *Cs-137* and *I-131* measured in Chiba City and Tsukuba City is compared with the predicted line based on the inventories at the reactor shutdown at 14:46 on March 11th and the radionuclide decay. The measured values are very close to the prediction on March 21st -March 22nd. This suggests that the peak around March 21st in the I-131 radioactivity concentration could result from the newly formed radioactivity plume by the core materials re-melt on March 20th -22nd at 1F. Furthermore, the peak around March 21st in the release rates estimation of *Cs-137* from the 1F site could be a consequence of this re-melt.

3.2. Analysis of the Unit 3 reactor

Since the initiation of injecting borated fresh water at 09:25 on March 13th, a large amount of water had been injected into the RPV of the Unit 3 reactor. And then it seemed as if the severely damaged core had been essentially cooled down even with most of its core material having once been molten. However, a detailed investigation of the measured data considering energy balance will reveal the actual situation. Injection flow rate is shown in Fig.4 in comparison with MDHRFR. It shows that injection flow rate is not enough to remove the decay heat on March 21st through March 24st. Considering that the injection rate probably would have been reduced earlier than 00:00 on March 21st, the re-melt could have started even on March 21st.

The molten material flows down and interacts with water in the bottom head of the lower plenum. Molten material of high radioactivity will have flowed out to the containment. The radioactive material is expected to be released to the environment.

Rapid dose rate increases or a sharp peaks assumed to be caused by this release, were observed at many monitoring points on March 21st , in 2F, Kitaibaraki City, Takahagi City, Mito City (all in Ibaraki prefecture) and Tokyo. The trend curves suggest that contamination at least in Ibaraki prefecture, Chiba prefecture and Tokyo is dominated by this release from the Unit 3 on March 21st. The peak around March 21st-22nd in the *I-131* air radioactivity concentration could also be a consequence of this release. Air radioactivity concentration ratio of *Cs-137* and *I-131* measured in Chiba City and Tsukuba City is shown in compared with the predicted line based on the inventories at the reactor shutdown at 14:46 on March 11th and radionuclide decay. The measured values are very close to the prediction on March 21st -March 22nd. This suggests that the peak around March 21st in *I-131* radioactivity concentration can result from the newly formed radioactivity plume on March 20th and March 21st in 1F. The *Xe* dose rate measured in Chiba City on March 21th, which was larger than 10^{-3}μSv/h could be a consequence of this release. Furthermore, the peak around March 21st in the release rates estimation of *Cs-137* from the 1F site could be a consequence of this re-melt. The absence of a peak in the dose rate of 1F around this time could be due to the opposite wind direction when monitoring was conducted at northern place of the main office building.

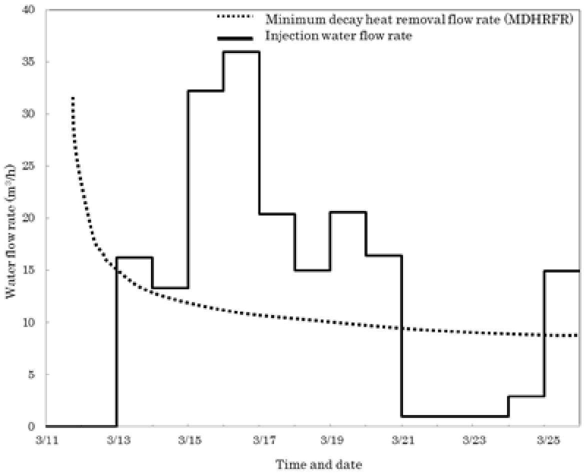


Fig. 4 Injection water flow rate in comparison with MDHRFR in the Unit 3.

3.3. Analysis of the Unit 2 reactor

From the start of injecting sea water on March 14th, a large amount of water had been injected into the RPV of the Unit 2 reactor. And then it seemed as if the severely damaged core had been essentially cooled down even with most of the core material having once been molten. However, a detailed investigation of the measured data considering energy balance will reveal the actual situation. Injection flow rate is shown in comparison with the MDHRFR in Fig. 5. It shows that injection flow rate cannot be enough, considering significant water flowing out/down through some breaks at the bottom of the lower plenum, to remove the decay heat on March 28th and thereafter. And then re-melt of the core materials could have occurred. With this re-melt, a large amount of radioactive materials is expected to be released to the environment. The peaks in the dose rate at 1F on March 29th and the sharp peak in Niigata City on March 31st could be a consequence of this release. The broad peak on March 29th through March 31st in the *I-131* air radioactivity concentration in Chiba City and Tsukuba City could also be a consequence of this release. Good agreement of the measured radioactivity concentration ratio of *Cs-137* and *I-131* with the prediction implies that the peak could be a consequence of the newly formed radioactivity plume by this re-melt. *Xe* dose rate measured in Chiba City on March 30th, which was larger than $10^{-3}\mu$Sv/h could be a consequence of this release. Furthermore, the peak around March 30th -31st in the release rates estimation of *I-131* and *Cs-137* from 1F site could be a consequence of this re-melt.

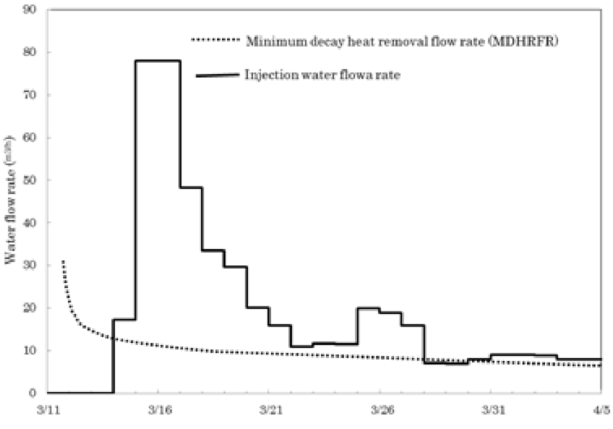


Fig.5 Injection water flow rate in comparison with MDHRFR in the Unit 2.

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 even after restarting the pump at 19:54 on March 14th through early morning on March 15th 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 March 14th 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[9]. Furthermore, the published TEPCO TV conference record suggests that the 1F NPS manager received the report on the fire pump out of working at 18:28[10]. Therefore it is quite highly probable that sea water should not have been injected even after the RPV depressurization around 18:00 on March 14th. 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[9]. Therefore it is also highly probable that sea water should not have reached the RPV even after restarting the pump at 19:54 through 15th early morning. The measured value of the shroud water level was below the bottom of the active fuel rods (BOF) from March 14th 18:22 through 21:18, which is consistent with the dry core assumption. The measured water level increases suddenly to higher than 0.3m from BOF after 21:20 through 23:11. However, it does not necessarily means that the water level is within the core, because the measured value of water level cannot correspond to the true level in the core degraded condition. Therefore, the measured water level after 21:20 could be spurious, and could reflect the RPV depressurization at 21:18. Then the dry core degradation 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 Unit-3 reactor building.

In the first TEPCO's Unit 2 analysis using the MAAP code, the total accumulated hydrogen generated is estimated about 360kg in the case 2[11]. 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 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. Japan Nuclear Energy Safety Organization (JNES) \performed a cross check analysis for the TEPCO's first analysis using MECOR code[12]. 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[13] and JNES[14], sea water injection rate are tuned in order to adjust the hydrogen generation rate fitting to the dry well pressure increase in the March 14th 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 have become far worse than the first analyses. For example, The RPV bottom failure is not calculated to occur, which is not consistent with the supposed condition.

4.3 Probability of re-melt of core materials

Just after a newspaper article publication on the author's re-melt hypothesis, TEPCO made a counterargument against it in the case of Unit 3[15]. They argued that the actual injection water flow rate might have been much larger than the released data (Fig. 4) which was measured on the accident management panel in the rector control room in the period from March 20th through 24th. In order to support the argument, injection water flow rate estimation based on fire pump outlet pressure was presented. It was larger than 55m^3/h. The rapid increase of dose rate observed in many cities on March 21st was suggested as due to rainfall. The interpretation was questionable because it could not explain the agreement between the prediction and observation on the air concentration ratio of Cs-137 to I-131 as well as the observation significant Xe-133. The re-melt hypothesis had been neglected in the accident investigation reports except the report of National Diet of Japan Fukushima Nuclear Accident Independent Investigation Commission (NAIC).[16] The NAIC report mentioned that the increase in dose rate on March 21st and 22nd might be due to core debris re-melt in the Unit 3.

Considering the high probability of bypassing of injected water to other facilities such as a condensate storage tank[9] and the large discrepancy between two measured values on injected water flow rate, it is highly probable that injection water flow rate could be less than the MDHRFR even before March 20th . It implies that core material re-melt might have occurred even before March 20th. Several observed data such as dose rate in the reactor containment, containment pressures and outside dose rate are consistent with this suggestion.

5 Conclusion

The author's analyses show that a phenomenological approach of accident investigation based on a simple model calculation and detailed analysis of measured data is very useful in order to understand the Fukushima accident process.

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