Spread of Explosion Product from Unit 1 and 3 Reactors of Fukushima Daiichi Nuclear Power Plant

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1 Introduction

Explosion of overheated nuclear reactor results in the release of the radioactive materials and heated fluids. In the case of the nuclear reactor emergency, the emergency services personnel would have been stationed upwind of the reactor so would not have suffered any significant radioactive fall-out. The emergency planning presumed that the released materials spread uniformly and flow downwind. In the case of the Fukushima Daiichi nuclear power plant, four people were injured during the explosion of unit 1 and eleven people were injured during the explosion of unit 3[1]. These injured people were exposed to the released fluid. In the recorded video, the most of the released fluid flows downwind. A white stream from the unit 3 reactor building flows upwind. In an overheated nuclear reactor, two fluids, water and gas are accumulated at an elevated pressure. The released fluid transports heat and momentum. Since liquid water has larger density than gas, the released liquid transports a larger amount of heat and momentum than gas. Considering the densities of liquid water and gas, it is worth to investigate how the released materials spread from the damaged nuclear reactor building. The horizontal scale of the recorded video is determined by the recently released drawing of the unit 4 reactor building [2-6]. The correlation peak of brightness between two sample pixels for 10 seconds gives the traveling time of the released materials crossing the sample pixels. Presuming the boundary layer flow near the ground, the traveling time and the separation between pixels give the horizontal flow velocity.

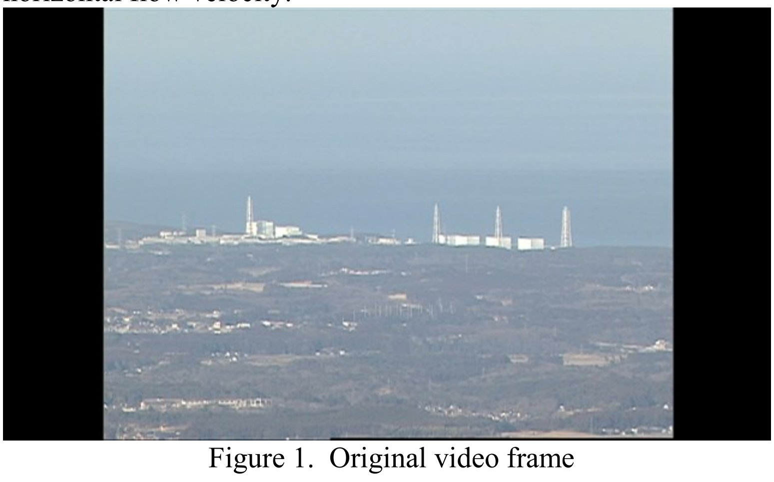
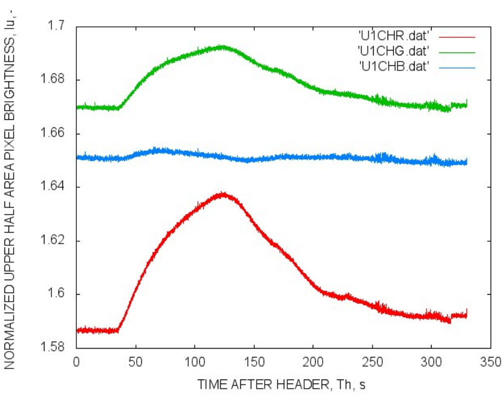


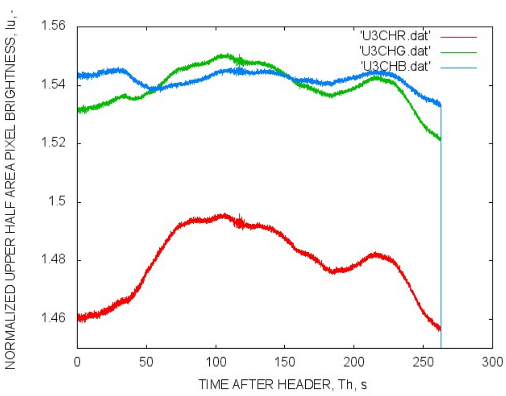
Figure 1. Original video frame

2 Recorded Spread of Released Fluid

The released fluid covers the background and the pixel brightness changes with time. The illumination conditions and the camera lens aperture also affect the pixel brightness. Figure 1 shows a frame of the used video. The horizon locates the center of the video frame as shown in fig. 1. Using the lower half of the video frame as the reference area, figure 2 shows the normalized pixel brightness of the upper half area for the red, green, blue components with time in figure 2. The normalized upper half area brightness increases at 35 s from the header. The explosion occurs at this time. The pixel brightness peaks near 120 s from the header for both cases. A small peak appears near 220 s from the header for the unit 3 case. The pixel brightness of blue component decreases partly due to covering the blue sky. The largest coverage effect of the background by the released fluid occurs in the red component. Due to longer wavelength, red light transmits better image than blue and green lights. The horizontal scale of two videos is determined by measuring the unit 4 building image. The horizontal scale is 0.85 m/pixel and the vertical scale is 0.78 m/pixel. The horizontal scale is 9 % larger than the vertical one. The estimated reading error of the building image is 3 %. The camera is viewing 35 degree from the north, approximately the middle of northeast and north northeast. Using the obtained horizontal and vertical scales, the velocity field projected on a plain normal to the viewing angle 35 degree from the north is determined.



UNIT 1 EXPLOSION



UNIT 3 EXPLOSION

Figure 2. Normalized upper half area pixel brightness

3 Released Materials Movement on Projected Plain

The horizontal length of the projected plain is 1200 m, the vertical length is 490 m from the ground level of the Fukushima Daiichi Nuclear power plant. The sampling pixels locate in 10 m intervals in horizontal and vertical directions. Correlations are taken for images of 10 seconds period with +/- 1.66 seconds time shift. The observable velocity is from +/- 150 m/s to +/- 6 m/s. The value of correlation is from 0 to 1. If the released materials travel without shape change, the observed value of correlation is 1. As the released materials mixed with the surrounding gas, the observed value of correlation reduces from 1 to 0. Comparing the original image with the correlation plot on projected plain, a threshold value, 0.5 is used to reconstruct the released materials image. If a smaller threshold value is used, the background noise covers the reconstructed released materials image. An edge image of the video frame is plotted in green with the released materials image in red for reference. The obtained released materials movement is plot on the projected plain with the elevation from the ground level of the Fukushima Daiichi Nuclear power plant and the horizontal distance from each exhaust tower. The distance between the unit 1 and unit 3 exhaust towers is 130 m on the projected plain. Figure 3 shows the released materials movement from T_h = 35 s to 45 s of the unit 1 reactor explosion. The horizontal distance from the unit 1 exhaust tower and the vertical distance from the ground level are shown in meters. The unit 1 reactor building locates at x = 0. A shallow dome image is seen at x = 0. The shallow dome image develops for T_h < 75 s and moves horizontally. From T_h = 85 s, the released materials at y = 200 m moves at the largest velocity. The leading edge of the released materials at y = 200 m reaches the video frame edge at T_h = 115 s. The upper edge of the released materials reaches y =350 m.

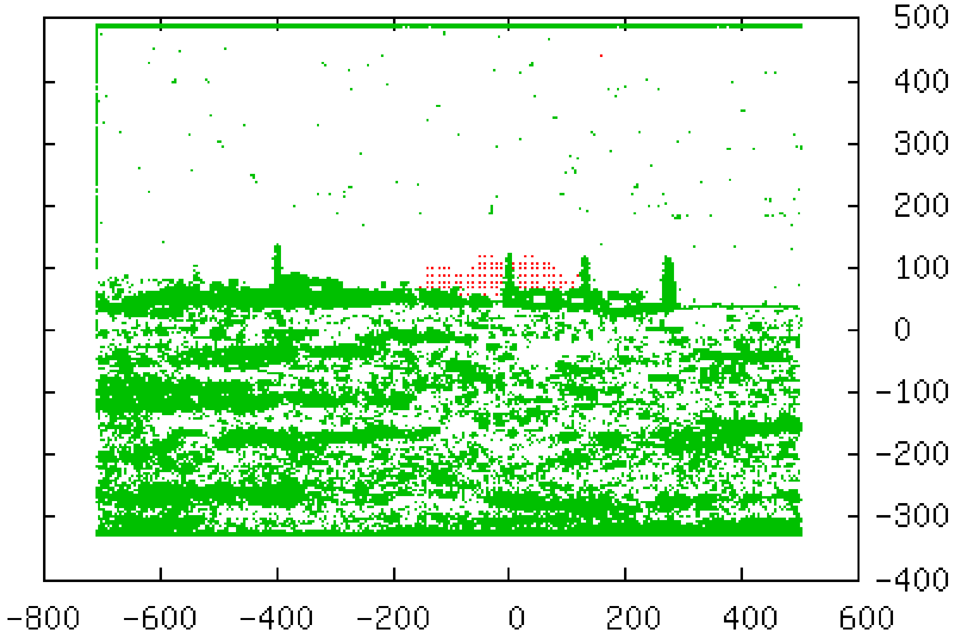


Figure 3. Released materials movement from T_h = 35 s to 45 s of unit 1 reactor explosion

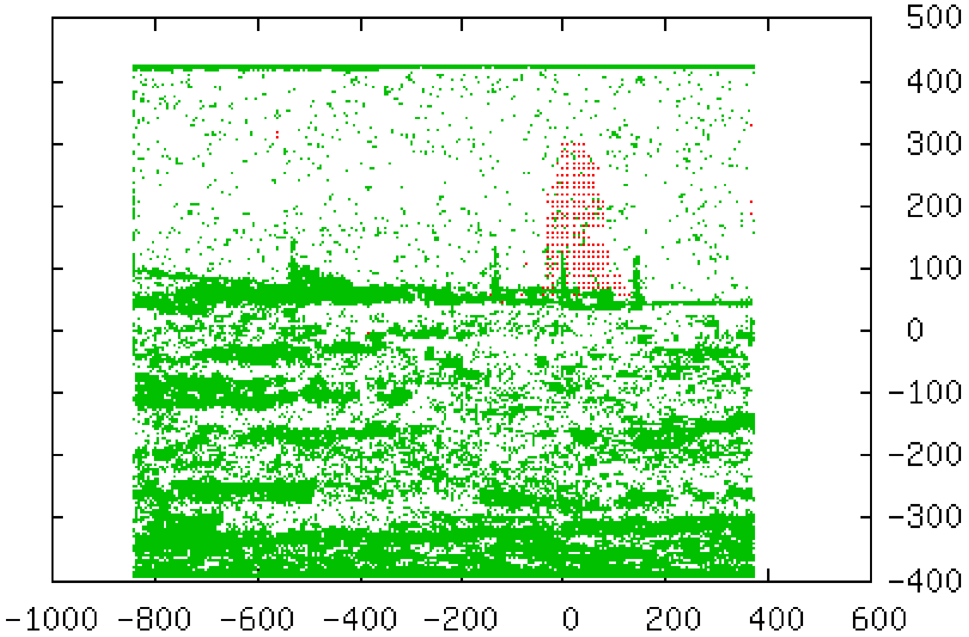


Figure 4. Released materials movement from T_h = 35 s to 45 s of unit 3 reactor explosion

Figure 4 shows the released materials movement from T_h = 35 s to 45 s of the unit 3 reactor explosion. A cone image is seen at x = 0. The upper edge of the cone reaches y = 300 m. The upper edge of the cone reaches the video frame edge at T_h = 55 s and the cone image moves horizontally at 5 m/s. From T_h = 55 s, the released materials at y = 200 m moves at the largest velocity. The leading edge of the released materials at y = 200 m reaches the video frame edge at T_h = 75 s. From T_h = 55 s to 105 s, the released materials are seen at the area between x = -130 m and 0 m where is the upwind of the reactor building unit 3.

Two series of the released materials movements are sliced in vertical direction. The mean horizontal position is determined with more than 8 points for each slice. Figure 5 shows the case of the unit 1 reactor explosion. The unit 1 reactor building locates at X = 0 in this figure. Area of -600 m < X < 400 and 0 < Y < 400 m is shown. The unit 4, 5 exhaust tower at X = - 400 m, the unit 3, 4 exhaust tower at X = 130 m are seen in this figure. This figure shows the edge image of the video frame before the explosions in red with the mean horizontal position line at every 10 second in green for reference. The mean horizontal position line deforms after T_h = 115 s when the leading edge of the released material reaches the video frame. The base of the mean horizontal position line moves – X direction and is fixed at x = - 200 m. The top area of the mean horizontal position line moves – X and + Y direction for 35 s < T_h < 115 s. The flow is rising from the sea to the hill. All mean horizontal position lines locate at X < 0 where is downwind of the exploded Unit 1 reactor building. The mean horizontal position line shows the boundary layer at Y < 250 m and the surface effect is seen at Y < 150 m. The roofs of buildings are working as vortex generators. One is at X = -150 m, another is at X = -350 m. The released materials are trapped near these vortex generators and slowly return into the flow. In 80 m > Y > 50 m and Y < 50 m, the released materials return from a trap. The most part of the released materials from the unit 1 reactor building is ejected during the explosion and trapped by the ground surface and the building walls.

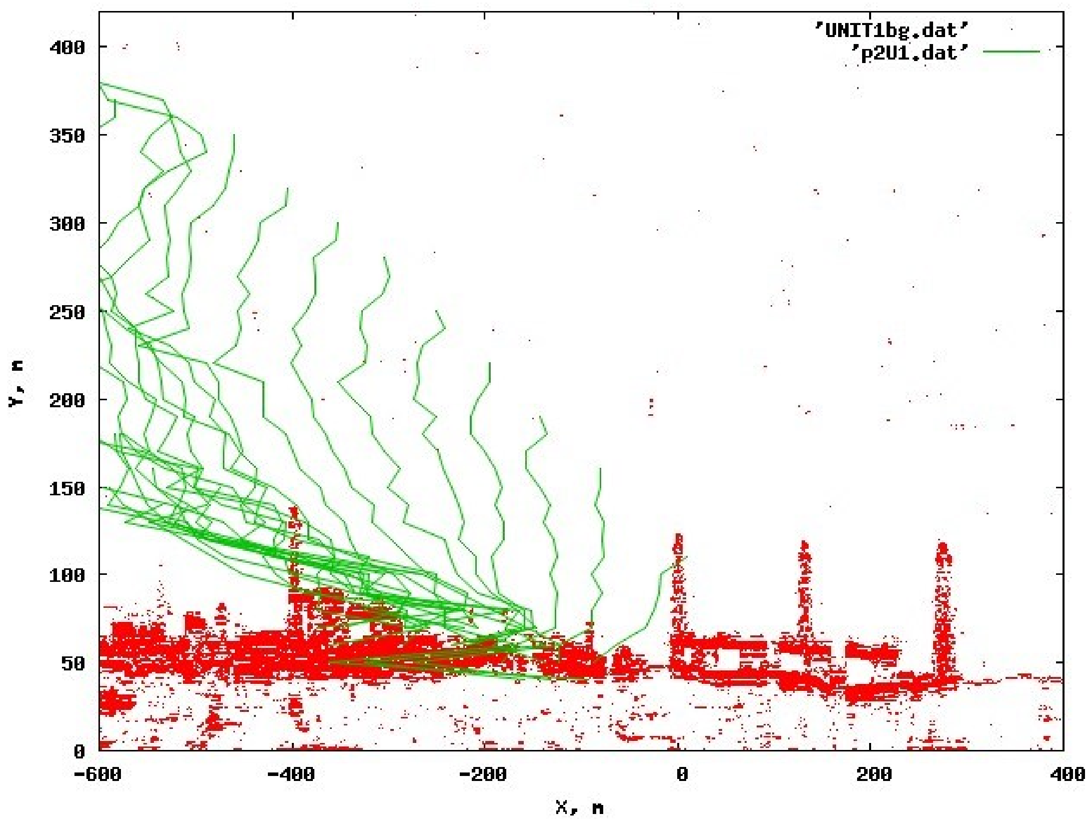


Figure 5. Mean horizontal position of released materials of Unit 1 reactor explosion case

Figure 6 shows the case of the unit 3 explosion. The unit 3 reactor building locates at X = 0. The unit 4, 5 exhaust tower at X = - 530 m, the unit 1, 2 exhaust tower at X = - 130 m are seen in this figure due to the reference point change to the unit 3. The mean horizontal position line also deforms after T_h = 75 s when the leading edge of the released materials reaches the video frame. There are two bases of the mean horizontal position lines, one is at X = - 300 m and another is at X = 0. The Unit 3 building locates at X = 0 and the base of the mean horizontal position lines at X = 0 is the destroyed unit 3 reactor building. The release of materials from the unit 3 reactor building continues for this period. The base of the mean horizontal position lines at X = - 300 m locates near the vortex generator observed in the unit 1 explosion at X = - 280 m (-150 m). The upper part of mean horizontal position line of Y > 200 m is moving at + 6 m/s. The roofs and exhaust towers are working as vortex generator and complicated mixing is seen at Y < 200 m. Excluding this small scale mixing, a clear boundary layer is seen in this area. Part of the released materials travels 300 m in the upwind direction and is accumulated on the ground surface and the building walls. In vertical direction, the released materials travel more than 400 m in the wake of fragments. In horizontal direction, the released materials travel 300 m along the ground. The vertical spread of the released materials from the vortex generator at X = - 280 m is slower than that of the unit 1 case with similar wind velocity. This slow spread shows the released materials at X = - 280 m have smaller diffusivity than that of the unit 1 case. The diffusion characteristic of the explosion products of the unit 1 and unit 3 cases are different under similar wind velocity. As shown in figure 5, the vertical movement is much larger in the unit 1 case and this rising flow from the sea contributes to enhance the vertical movement. The appearance of the released materials at -300 < X < 0 is white in the unit 3 case and moves to the upwind direction. The composition of the unit 3 case seems to be largely different from that of the unit 1 case. The white color materials are seen to filling the lower part of the nuclear power plant. The behavior of these materials is identical with that of the condensed water vapor cloud, which forms after the nuclear reactor core damage scenario.

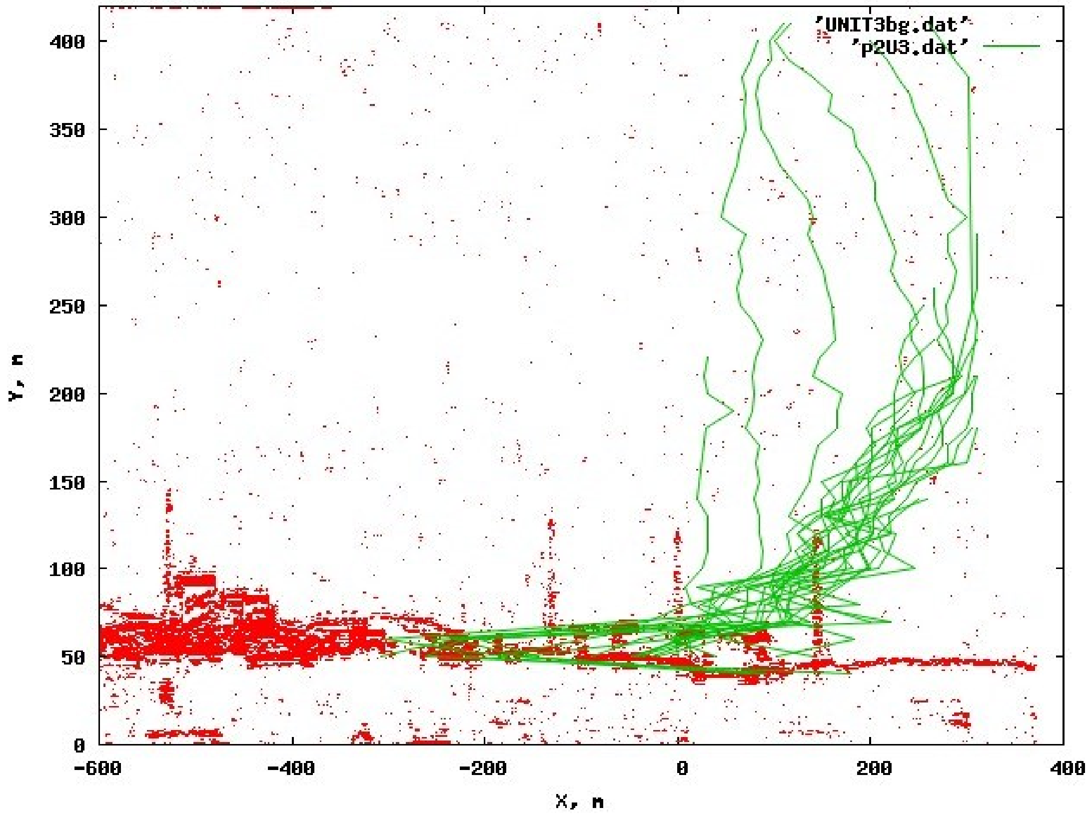


Figure 6. Mean horizontal position of released materials of Unit 3 reactor explosion case

4 Conclusions

Two series videos were examined with correlations with 10 m intervals and movement of the released materials are determined. By tracing the movement in horizontal direction, the flow field near the damaged reactor buildings is obtained. The boundary layer is seen between the ground level and 200 m. The wind velocities at the edge of the boundary layer is – 6 m/s for the unit 1 case and + 6 m/s for the unit 3 case. In the unit 1 case the rising flow from the sea is seen. The ground elevation and the wind direction could affect the mixing characteristic. For the unit 3 case, the released materials travel 300 m in the upwind direction on the used projected plain. Considering the observation angle and the ground elevation of the Fukushima Daiichi nuclear power plant, the release materials could travel two or three times of distance in upwind direction of this observed length. For the safety assessment for the emergency services personnel, a series of detailed flow analysis with the overheated nuclear reactor scenarios in the nuclear power plant should be carried out with the flow field observation records at the plant site.

Acknowledgements

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