Institute for Science and International Security

ISIS REPORT

FUKUSHIMA CRISIS: UNMONITORED RELEASES
Preliminary Assessment of Accident Sequences and Potential Atmospheric Radiation Releases

By David Albright, Paul Brannan, and Christina Walrond
March 31, 2011

The following chronology details events at the Fukushima Daiichi nuclear reactor station in Japan from March 11-25, 2011. It includes notable radiation spikes and corresponding wind patterns, as well as satellite imagery of the plant. All reported times correspond with local time in Japan.

ISIS has collected data to better understand atmospheric radiation releases, ground level wind patterns, and instances of unmonitored radiation releases to the atmosphere from the Fukushima Daiichi nuclear reactors. The radiation readings and ground level wind directions are from the TEPCO web site. ISIS could not validate TEPCO's information, but the data appear adequate to conduct some scoping analysis of the releases. Using this information, ISIS has sought to understand the fate of the releases and determine whether radiation monitoring stations intersected the plume of released radioactive material. We welcome any input.

Since March 11, reactor units 1-4 at the Fukushima Daiichi nuclear plant have experienced hydrogen explosions, fires, partial melting of irradiated or "spent" fuel in the reactors, the uncovering and possible burning of irradiated fuel in spent fuel ponds at reactor 4 and perhaps other reactors. Table 1 lists several known accidents that occurred through March 18. These accidents, and perhaps ones that were not noticed or reported, released significant amounts of radiation into the atmosphere that the winds spread widely. They all require greater scrutiny.

From an analysis of the limited data on atmospheric releases, ISIS has developed several key findings. The first is that the limited radiation detection capabilities at the Fukushima Daiichi plant following the earthquake and tsunami eliminated the ability to detect, characterize, or track a release of radiation. Many releases went partially or completely undetected by on-site monitoring. None of the releases from accidents were monitored as to their radioactive contents. Although the amount and type of radionuclides in these releases cannot be estimated from the existing on-site monitoring data, the existing data support that the potential for significant radiation doses to off-site population exists, particularly in sectors northwest and southwest of the reactors.

Second, ground level winds often blew inland in the days immediately after the earthquake, contrary to many reports that stated that the radiation was carried out to sea by prevailing winds. While prevailing winds would also have an effect on the longer-range dispersal of radiation, the area outside the plant received elevated levels of radiation as a result of these local wind patterns. In the first 24-48 hours after the shutdown of the reactors, these releases would have contained significantly more radioactivity due to relatively short-lived volatile and gaseous radionuclides.

236 Massachusetts Avenue, NE, Suite 305 Washington, DC 20002
TEL 202.547.3633 • FAX 202.547.3634
E-MAIL isis@isis-online.org • www.isis-online.org

As a result, these releases could have resulted in higher doses to the local population than has been assumed. The most affected would be those closer to the reactors caught in the plume of radiation coming from the accidents, such as people who had not yet evacuated beyond 20 kilometers of the site. However, others outside this 20-kilometer radius could have also received significant doses from the radioactive plumes emanating from the reactors.

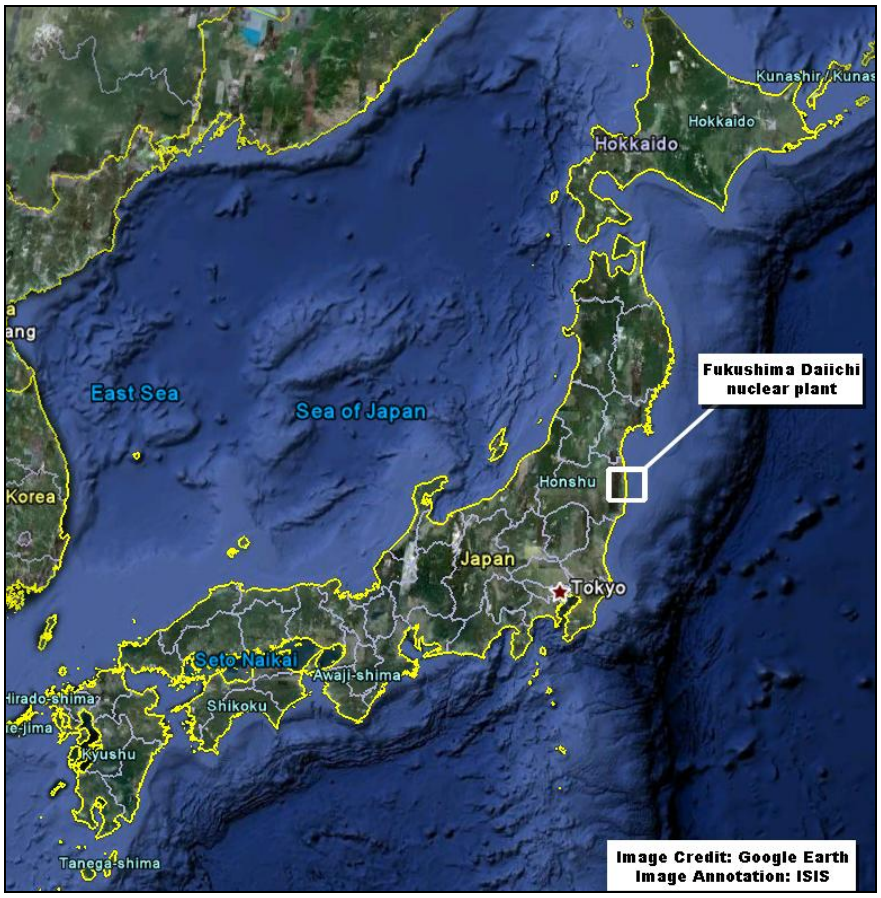
Third, the existing monitoring data support that the largest off-site atmospheric releases occurred prior to March 18 or 19. From then through March 25, the end date of this study, atmospheric releases appear to have diminished substantially. However, the potential for large atmospheric releases remains without significant intervention to cool the reactors and spent fuel ponds of units 1-4. Moreover, releases into the sea and ground water have increased as a result of all the water spraying of the reactor buildings.

Fourth, the releases need to be better assessed as to their amounts, radioactive content, and off-site transport in order to better identify exposed populations and determine their radiation doses and health risks. The Japanese government should start assembling an expert group that can credibly assess the releases and risks to the population and communicate its findings to the Japanese public. To enhance its credibility, this group should include experts that are independent of the nuclear power industry.

Fifth, in order to reduce the occurrences of partially monitored and unmonitored releases, a priority should be repairing or deploying on-site monitoring stations and more frequently characterizing atmospheric emissions from the site and their fate. Although authorities are monitoring more consistently now, they need to reestablish systematic routine monitoring as soon as possible so as to better warn of any releases from the damaged reactors and spent fuel ponds and alleviate public anxiety about additional radiation releases.

Table 1. Summary of Known Accident Data: Through March 18

REACTOR	DATE	TIME	DESCRIPTION
Unit 1	03/12	10:20	Internal pressure problem reported
		15:36	Explosion heard
Unit 2	03/12	10:20	Internal pressure problem reported
	03/15	06:20	Explosion
		10:30	Inject water into reactor vessel; vent the drywall
	03/16	On-going	Steam venting from side of building
	03/17	On-going	Steam venting from building
	03/18	On-going	Steam venting from building
Unit 3	03/13	09:20	Opening of pressure vent valve
	03/14	11:01	Explosion
	03/16	On-going	Steam rising from building
		18:00 and other cases	Smoke and/or steam vents from building
	03/17	On-going	Steam venting from building
Unit 4	03/15	06:00	Explosion
		~10:30	Fire in spent fuel pond
	03/16	05:45	Fire, which extinguished itself



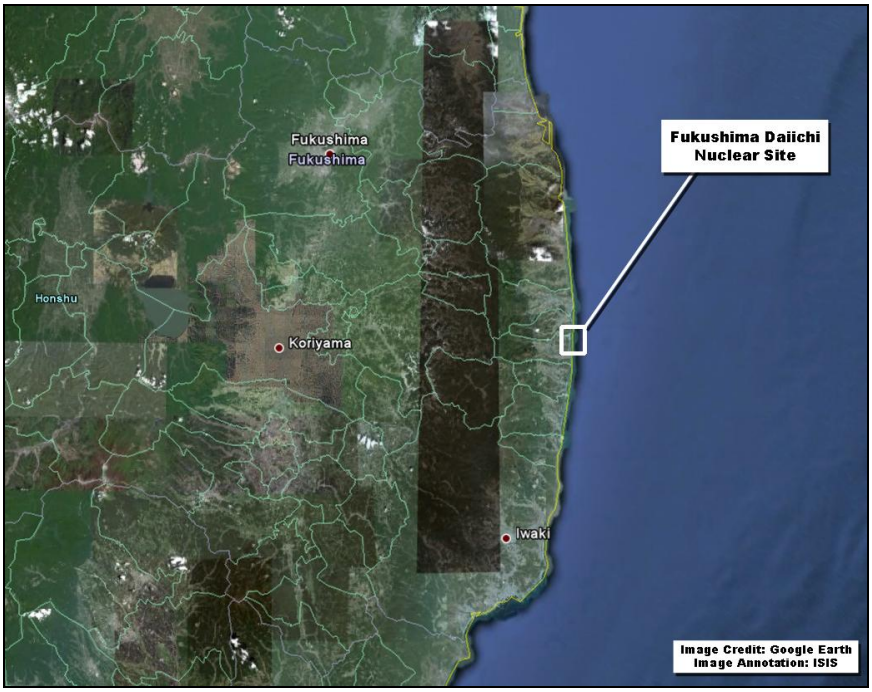


Figure 1. A map of Japan showing the location of the Fukushima Daiichi nuclear power station and a regional view of the area surrounding the Fukushima Daiichi nuclear site.

Limited Radiation Monitoring

The following map of the Fukushima Daiichi nuclear station shows the location of the routine radiation monitoring posts (MP) arranged around the perimeter of the site (see figure 2). During normal operations, these monitoring posts record radiation levels and characterize releases that would affect the local population. However, all but one of these monitoring posts were rendered inoperative by the earthquake and tsunami and the resulting loss of electricity. In addition, radiation monitoring equipment at the reactor buildings was also damaged and unable to provide basic information about the radiation releases or "source terms" which are the amount and type of radioactive material emitted during the accidents.

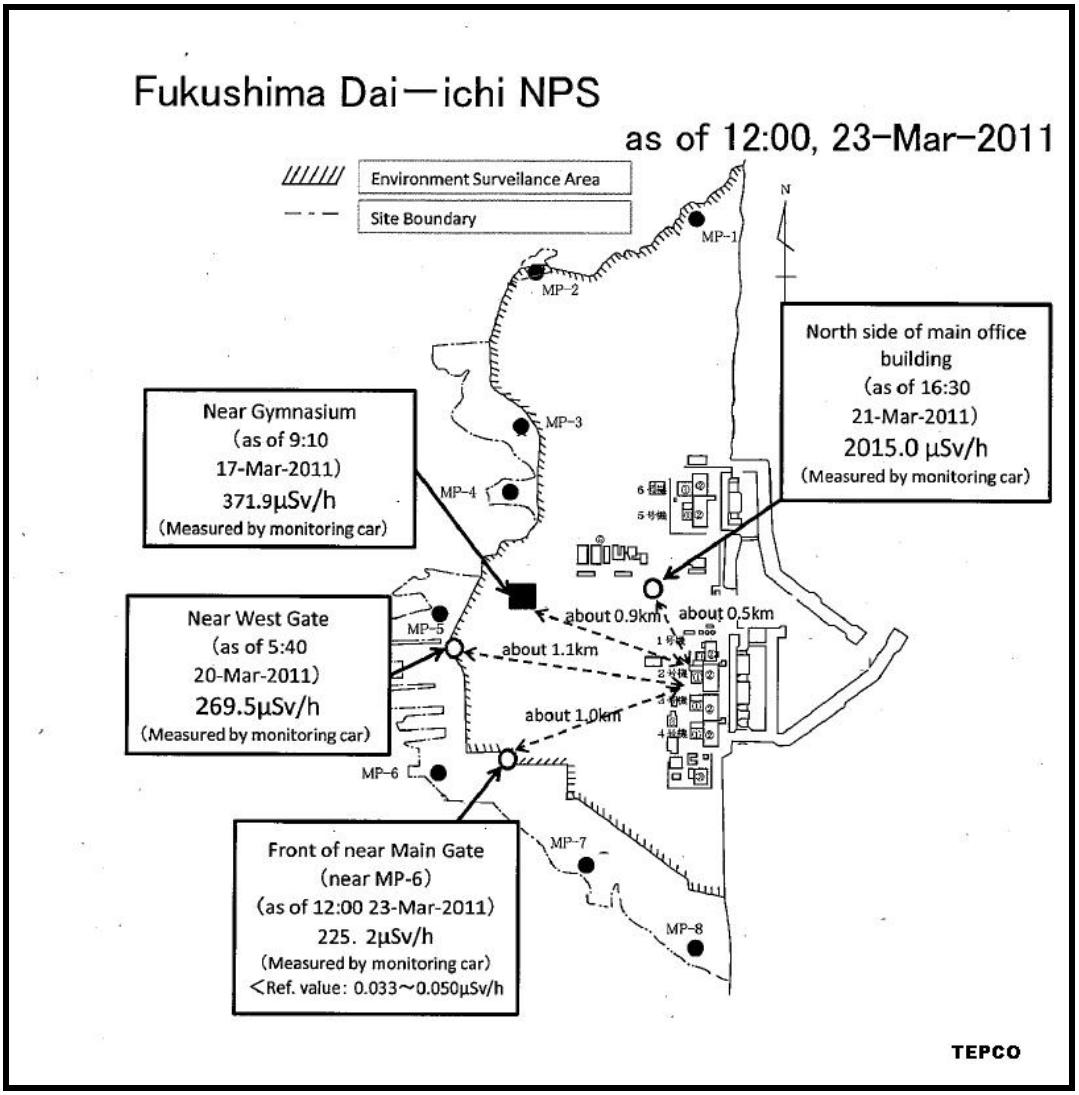


Figure 2. Map of immediate area surround the reactors. The annotations list four specific radiation readings recorded several days after releases started that were taken by a mobile monitoring unit.

After the accident, TEPCO was unable to re-activate these damaged monitoring capabilities with one possible exception. It may have re-established one stationary monitoring post at the main gate.

In place of the non-functional stationary monitoring posts, TEPCO started using a car or cars equipped with monitoring equipment. The car has driven around the compound at Fukushima Daiichi and has taken readings at various times and locations.

After the tsunami, the car typically took readings at or near about half of the original monitoring posts, including the fixed station at the main gate. However, these monitoring points are closer together and do not intersect all the releases that occurred.

Most of the available radiation readings have been taken at points generally west of the reactor buildings, and not much further north or south of the reactors. The monitoring stop near the "main office building" is further north of the reactors; however, there are only sporadic readings from this post on any given day, and there are no readings from this post on some days. For example, if a release were to occur at reactor unit 2 with winds out of the south, for example, and if the monitoring car were at the main gate approximately 1 kilometer south-west of unit 2, the release would go unmonitored until the wind shifted to a northerly direction. With the apparent inability to monitor at more than two spots on site at the same time and large amounts of unmonitored areas at the reactor site, there have been releases that have been missed or have been only partially detected.

There were instances in which readings have occurred at two different posts at the same time; but it was rare, and the majority of readings occurred without any accompanying readings from other stations at the same time. With only one data point reported for most time periods, it is impossible to be certain of the number and extent of releases. The wind direction during and preceding a release can give some indication of the initial direction of a release; however, without the context of other readings from around the site, it is difficult to determine if a spike is the result of a release blowing towards a monitoring station, or a much larger release only partially detected. This lack of context also makes it difficult to interpret a spike as a new release or the result of changing winds.

A priority is establishing more comprehensive radiation monitoring at the site that would allow a more thorough understanding and detailed analysis of the releases. In addition, the radiation releases, particularly those in the early days of this accident, need better characterization in order to determine the doses and health risks to the off-site population.

Daily Readings and Observations

March 11

14:46 - 9.0 magnitude earthquake occurs off of the coast of Japan, creating a 14-meter tsunami. All reactors shut down.

19:46 - The government reveals a cooling problem at Fukushima Daiichi and orders residents within 2 km radius to evacuate.

21:49 - Jiji News Agency reports that the evacuation radius has been extended to 3 km.

March 12

06:50 - Order issued to control the internal pressure of containment vessels of **units 1 and 2.**

wind direction from: west-northwest, changing to south
radiation level: 2.47 µSv/h at MP-8

15:36 - Sound of explosion in **unit 1.**

wind direction from: south, changing to south-southeast
radiation level: 8.23 µSv/h at main gate
3.33 µSv/h at MP-8

Note: Due to wind direction, these monitoring stations did not intersect the initial plume. Data from most relevant monitoring stations is unavailable in the TEPCO data posted on its web site, http://www.tepco.co.jp/en/nu/monitoring/index-e.html.

Notable Radiation Changes on March 12[1]

TIME	RADIATION LEVEL	MONITORING STATION	WIND DIRECTION
00:00	0.062 µSv/h	Main Gate	Southeast
06:40	4.92 µSv/h	Main Gate	West-Northwest
10:10	6.65 µSv/h	Main Gate	Southeast
10:20	180.2 µSv/h	Main Gate	Southeast
10:30	385.5 µSv/h	Main Gate	North
10:40	162.9 µSv/h	Main Gate	North
11:30	35.77 µSv/h	Main Gate	East
15:10	6.99 µSv/h	Main Gate	South
15:20	5.59 µSv/h	Main Gate	Southwest
15:30	5.49 µSv/h	Main Gate	South
15:40	8.23 µSv/h	Main Gate	South
15:50	5.311 µSv/h	Main Gate	South
16:00	5.29 µSv/h	Main Gate	South-Southeast
16:10	3.64 µSv/h	Main Gate	South-Southeast
16:20	3.43 µSv/h	Main Gate	South-Southeast
16:30	3.32 µSv/h	Main Gate	South
	Radiation levels remain relatively constant.		
23:50	3.07 µSv/h	Main Gate	Northwest
15:10	3.33 µSv/h	Nearby MP-8	No Data
15:20	3.23 µSv/h	Nearby MP-8	No Data
15:30	3.21 µSv/h	Nearby MP-8	No Data
15:40	3.33 µSv/h	Nearby MP-8	No Data
15:50	2.19 µSv/h	Nearby MP-8	No Data
16:00	2.22 µSv/h	Nearby MP-8	No Data

[1] Not all radiation readings in the TEPCO data are included in this table. The purpose of this table is to highlight significant increases in radiation and wind directions. The complete tables can be found at the TEPCO web site.

16:10	2.20 µSv/h	Nearby MP-8	No Data
16:20	2.18 µSv/h	Nearby MP-8	No Data
16:30	2.12 µSv/h	Nearby MP-8	No Data
20:30	\Wind data from different monitoring station	Main Gate	Southwest
20:40	5.0 µSv/h	Nearby MP-8	No Data
20:50	6.0 µSv/h	Nearby MP-8	No Data
21:50	Wind data from different monitoring station	Main Gate	Southwest
21:00	80.0 µSv/h	Nearby MP-8	No Data
22:00	Wind data from different monitoring station	Main Gate	Northwest
22:00	70.0 µSv/h	Nearby MP-8	No Data
22:30	Wind data from different monitoring station	Main Gate	West
22:30	4.87 µSv/h	Nearby MP-8	No Data

Observations

By dawn on the day after the earthquake, the radiation readings at the main gate were already 100 times higher than the area's baseline radiation reading, implying the onset of unexpected radiation releases from the reactors. As the wind shifted during the morning, coming from the north, the radiation measurements at the main gate increased and then decreased, further implying that the reactors were releasing radiation into the atmosphere, much of which was unmonitored as it blew north earlier in the morning.

The releases following the explosion at 3:36pm in reactor unit 1 do not appear to have been monitored initially. For the first hour after the explosion, the winds were blowing from the south or southeast at about 5-7 miles per hour, carrying the radiation up the coast or inland. The wind direction is not given in TEPCO's data for the next four hours. At 8:30pm, the wind direction is from the southwest and shifts to the northwest by about 11:30pm.

At 9:00pm, radiation readings at MP-8 increase ten-fold, apparently after the wind shifted towards the south. The increase could have resulted from the release from unit 1 or a new release.

Much of the radiation emitted after the explosion in unit 1 may have blown to the northwest of the reactor. This plume, which would have contained a relatively large amount of short-lived radionuclides, could have produced significant radiation exposures to members of the off-site population who were caught outside.

March 13

05:41 - The IAEA reports that 170,000 people have been evacuated in a 20 km radius around Fukushima Daiichi. The evacuation radius was incrementally increased on March 12.

09:20 - Opening of pressure vent valve of **unit 3**

wind direction from: south-southwest, changing to west-northwest, changing to north
radiation level: 281.70 µSv/h at main gate
27 µSv/h at MP-1
76.9 µSv/h at MP-4

13:12 - Fresh water injection switched to seawater injection in **unit 3** through Fire Extinguishing Safety Line.

wind direction from: southwest, changing to west-northwest, changing to north-northwest
radiation level: 4.907 µSv/h at main gate
17 µSv/h at MP-1
43.5 µSv/h at MP-4

Notable Radiation Changes on March 13

TIME	RADIATION LEVEL	MONITORING STATION	WIND DIRECTION
00:00	3.16 µSv/h	Main Gate	Northeast
08:50	15.900 µSv/h	Main Gate	Southeast
09:00	10.240 µSv/h	Main Gate	South-Southeast
09:10	175 µSv/h	Main Gate	East
09:20	281.7 µSv/h	Main Gate	South-Southwest
09:30	26.0 µSv/h	Main Gate	North
10:00	6.512 µSv/h	Main Gate	Northwest
08:10	100 µSv/h	Nearby MP-1	No Data
08:30	80 µSv/h	Nearby MP-1	No Data
08:50	90 µSv/h	Nearby MP-1	No Data
09:00	37 µSv/h	Nearby MP-1	No Data
16:00	Wind data from different monitoring station	Main Gate	Southeast
16:00	31 µSv/h	Nearby MP-1	No Data
16:10	Wind data from different monitoring station	Main Gate	South
16:10	45 µSv/h	Nearby MP-1	No Data
16:20	Wind data from different monitoring station	Main Gate	South
16:20	150 µSv/h	Nearby MP-1	No Data
16:30	Wind data from different monitoring station	Main Gate	Southeast
16:30	46 µSv/h	Nearby MP-1	No Data
18:50	Wind data from different monitoring station	Main Gate	North-Northwest

18:50	25 µSv/h	Nearby MP-1	No Data
20:10	Wind data from different monitoring station	Main Gate	Southwest
20:10	450 µSv/h	Nearby MP-2	No Data
21:20	Wind data from different monitoring station	Main Gate	North
21:20	440 µSv/h	Nearby MP-2	No Data
22:40	Wind data from different monitoring station	Main Gate	Northeast
22:40	430 µSv/h	Nearby MP-2	No Data
23:50	Wind data from different monitoring station	Main Gate	West
23:50	410 µSv/h	Nearby MP-2	No Data
09:00	143.5 µSv/h	Nearby MP-4	East-Northeast
09:20	76.9 µSv/h	Nearby MP-4	West-Northwest
10:30	58 µSv/h	Nearby MP-4	Northwest
12:50	45.2 µSv/h	Nearby MP-4	North-Northwest
13:30	42.9 µSv/h	Nearby MP-4	Northwest
13:40	44.0 µSv/h	Nearby MP-4	Northwest
13:50	905.1 µSv/h	Nearby MP-4	East-Northeast
14:00	499.3 µSv/h	Nearby MP-4	South
14:10	646 µSv/h	Nearby MP-4	East-Southeast
14:40	133 µSv/h	Nearby MP-4	South-Southeast
15:00	58.7 µSv/h	Nearby MP-4	South-Southeast
15:40	56.5 µSv/h	Nearby MP-4	East-Northeast
15:50	76.1 µSv/h	Nearby MP-4	South-Southeast
16:00	107.1 µSv/h	Nearby MP-4	South
16:10	58.0 µSv/h	Nearby MP-4	South
16:30	71.5 µSv/h	Nearby MP-4	South-Southeast
16:40	57.2 µSv/h	Nearby MP-4	South-Southwest
16:50	100.1 µSv/h	Nearby MP-4	Southeast
17:10	60.8 µSv/h	Nearby MP-4	Southwest
18:40	47.3 µSv/h	Nearby MP-4	North
23:51	37.9 µSv/h	Nearby MP-4	North-Northwest

Observations

Based on the wind direction and speed, it is unlikely that any of the spikes in radiation documented in the table correspond with the venting of steam from reactor 3, whose upper structure remained intact on the 13th. However, venting likely continued from reactor 1, which would explain the elevated levels at the monitoring locations.

The radiation readings at several locations, including the main gate, MP-1, MP-2, and MP-4, fluctuated throughout the day as does the wind direction. But the measured radiation values were steadily increasing, reaching over 900 µSv/hr at 1:50pm at MP-4, northwest of the reactors. The increase follows what appear to be winds from the northwest and east-northeast, implying the blowing back of a radioactive plume released earlier. Similarly, a spike occurs after 8:00pm at MP-2, northwest of the reactors.

March 14

11:01 - Explosion in **unit 3**

wind direction from: north-northwest, reported at 10:51am
*radiation level: 50.387 μSv/h at main gate**

11:04 - Steam seen venting out of **unit 3** building in satellite image. Smoke or dust plume from the explosion three minutes earlier also seen above building. Substantial structural damage to **unit 3** building from explosion can be seen. The top portion of **unit 1** building shows damage from explosion as well.

Figure 3. Satellite image taken at 11:04am March 14, approximately three minutes after explosion at unit 3 building. Smoke or dust plume from explosion at unit 3 building can be seen extending out to the sea, wind direction from the west.

Notable Radiation Changes on March 14

TIME	RADIATION LEVEL	MONITORING STATION	WIND DIRECTION
00:00	4.855 µSv/h	Main Gate	West
02:00	4.3565 µSv/h	Main Gate	Southeast
02:10	4.594 µSv/h	Main Gate	Northeast
02:20	751.2 µSv/h	Main Gate	Northwest
02:30	433.0 µSv/h	Main Gate	South
02:50	66.27 µSv/h	Main Gate	East-Northeast
03:20	15.43 µSv/h	Main Gate	West
10:35	Wind data from different monitoring station	Nearby MP-4	Northwest
10:41	Wind data from different monitoring station	Nearby MP-4	Northwest
10:51	Wind data from different monitoring station	Nearby MP-4	North-Northwest
11:37	50.387 µSv/h	Main Gate	North-Northeast
11:44	19.6 µSv/h	Main Gate	No Data
12:06	10.816 µSv/h	Main Gate	North-Northeast
21:20	6.0 µSv/h	Main Gate	Northwest
21:25	6.8 µSv/h	Main Gate	Southwest
21:30	29.7 µSv/h	Main Gate	Southeast
21:35	760.0 µSv/h	Main Gate	Southeast
21:37	3130 µSv/h	Main Gate	South
22:15	431.7 µSv/h	Main Gate	North
22:50	267 µSv/h	Main Gate	North-Northeast
23:35	211.3 µSv/h	Main Gate	North-Northeast
23:55	192.3 µSv/h	Main Gate	West
00:00	Wind data from different monitoring station	Main Gate	West
00:00	410 µSv/h	Nearby MP-2	No Data
02:50	Wind data from different monitoring station	Main Gate	East-Northeast
02:50	490 µSv/h	Nearby MP-2	No Data
03:10	Wind data from different monitoring station	Main Gate	West
03:10	650 µSv/h	Nearby MP-2	No Data
03:30	Wind data from different monitoring station	Main Gate	Southeast
03:30	720 µSv/h	Nearby MP-2	No Data
04:00	Wind data from different monitoring station	Main Gate	North
04:00	820 µSv/h	Nearby MP-2	No Data
04:10	Wind data from different monitoring station	Main Gate	West-Northwest
04:10	450 µSv/h	Nearby MP-2	No Data
05:00	Wind data from different monitoring station	Main Gate	Southwest
05:00	400 µSv/h	Nearby MP-2	No Data

08:30	287.2 µSv/h	Nearby MP-3	West
08:50	268 µSv/h	Nearby MP-3	South-Southwest
09:00	304.8 µSv/h	Nearby MP-3	South-Southwest
09:12	518.7 µSv/h	Nearby MP-3	Southeast
09:40	293.7 µSv/h	Nearby MP-3	South
10:40	261.9 µSv/h	Nearby MP-3	West
14:30	231.1 µSv/h	Nearby MP-3	Northwest
00:01	38.2 µSv/h	Nearby MP-4	Northwest
02:10	36.5 µSv/h	Nearby MP-4	East-Southeast
02:20	44.6 µSv/h	Nearby MP-4	North-Northwest
02:30	319.3 µSv/h	Nearby MP-4	North
03:00	144.2 µSv/h	Nearby MP-4	North
04:00	68.8 µSv/h	Nearby MP-4	North-Northeast
05:41	38.3 µSv/h	Nearby MP-4	West-Northwest
09:25	87.083 µSv/h	Nearby MP-4	South-Southwest
09:43	48.889 µSv/h	Nearby MP-4	Southwest
14:14	29.8 µSv/h	Nearby MP-4	Northwest

- Workers withdrawn from the plant due to increased radiation levels. Radiation level reporting areas truncated.

Observations

The smoke and dust plumes from the explosion at reactor building 3 can be seen at 11:04am extending out over the sea—the image was taken approximately three minutes after the explosion. Thus, the winds close to the time of the explosion were heading to the east (wind direction from the west), towards the ocean. This is consistent with the wind direction from the west-northwest reported at 11:37am.

There was a large spike in radiation readings at about 9:30 pm at the main gate. The origin of this spike or its accuracy is unclear.

March 15

06:00 - Explosion in **unit 4**. This explosion was most likely caused by hydrogen produced in the spent fuel pond, since all the fuel rods had been transferred to the spent fuel pond in November 2010. The explosion in the **unit 4** reactor building was likely caused by a buildup of hydrogen resulting from a reaction between the zirconium cladding on the fuel and the steam from the pond.

wind direction from: north
radiation level: 73.2 µSv/h at main gate
38.4 µSv/h near MP-4

06:20 - Explosion occurred in **unit 2**, likely in the suppression chamber

wind direction from: northeast
radiation level: 807.7 µSv/h at main gate
22.7 µSv/h near MP-4

10:30 - A METI directive ordered TEPCO to extinguish fire in the spent fuel pond of **unit 4** and prevent the occurrence of re-criticality.

The same directive ordered TEPCO to inject water immediately into the reactor vessel of **unit 2** and vent the drywell, which is part of the containment of the reactor, possibly releasing more radioactivity.

wind direction from: northeast, changing to southeast
radiation level: 8,837.0 µSv/h at main gate
(see figure 1)

Workers are temporarily evacuated due to a 400 mSv/hr on-site reading, but they returned later in the day.

Notable Radiation Changes on March 15

TIME	RADIATION LEVEL	MONITORING STATION	WIND DIRECTION
00:00	188.9 µSv/h	Main Gate	West-Northwest
05:20	67.4 µSv/h	Main Gate	North-Northwest
08:20	807.7 µSv/h	Main Gate	Northeast
08:31	8,217.0 µSv/h	Main Gate	Northeast
08:40	1,726.0 µSv/h	Main Gate	North
08:50	2208.0 µSv/h	Main Gate	North
09:00	11,930.0 µSv/h	Main Gate	North-Northeast
09:35	7,241.0 µSv/h	Main Gate	Northeast
10:15	8837.0 µSv/h	Main Gate	No Data
12:05	Wind data from different monitoring station	West Gate	Southeast
12:25	1407.0 µSv/h	Main Gate	East-Southeast
13:30	1,068.0 µSv/h	Main Gate	South
15:00	649 µSv/h	Main Gate	Southeast
16:00	531.6 µSv/h	Main Gate	South
20:00	347.0 µSv/h	Main Gate	South
22:30	431.8 µSv/h	Main Gate	Southeast
23:00	4548.0 µSv/h	Main Gate	West
23:10	6960.0 µSv/h	Main Gate	North
23:15	2761.0 µSv/h	Main Gate	South

23:20	3648.0 µSv/h	Main Gate	East
23:25	4976.0 µSv/h	Main Gate	Northwest
23:30	8080.0 µSv/h	Main Gate	Northwest
23:35	6308.0 µSv/h	Main Gate	East
23:40	6592.0 µSv/h	Main Gate	North-Northwest
23:45	6847.0 µSv/h	Main Gate	North-Northwest
23:50	6066.0 µSv/h	Main Gate	East
23:55	7966.0 µSv/h	Main Gate	Northeast
09:35	Wind data from different monitoring station	Main Gate	Northeast
11:40	253.8 µSv/h	West Gate	No Data
11:45	162.4 µSv/h	West Gate	No Data
12:05	2431.0 µSv/h	West Gate	Southeast
12:15	2434.0 µSv/h	West Gate	East

Observations

The monitors recorded large radiation dose rates on the 15th. At 9 am, the radiation levels at the main gate peaked at almost 12,000 µSv/h. This radioactive plume likely resulted from the explosion in unit 4 and suspected fire in the spent fuel pond. The winds were from the north, northeast, blowing the radioactive material toward the south and southwest, intersecting the main gate. At about noon, the wind direction shifted to the south, southeast, and the radiation levels at the main gate went down. When the wind shifted back to northerly directions late in the day, the radiation levels increased again at the main gate. These readings imply that the reactors could have released large amounts of radiation during much of the day, and the monitoring stations detected these releases sporadically based on the wind direction and speed. The initial plume tended toward the south, southwest and later emissions blew to the north, northwest.

Figure 4 from the IAEA graphs the readings at MP-6, which is likely the same data as listed as the main gate on the TEPCO web site. The IAEA shifts the times to the UTC time zone, which is nine hours earlier. Three peaks are visible in the readings. In Japanese local time, the first two occur on the 15th and the third is on the 16th (see below). As discussed above, the first two spikes may reflect near continuous releases during the day, which were detected at this particular location as a result of the wind shifting so as to blow the releases over this monitoring point.

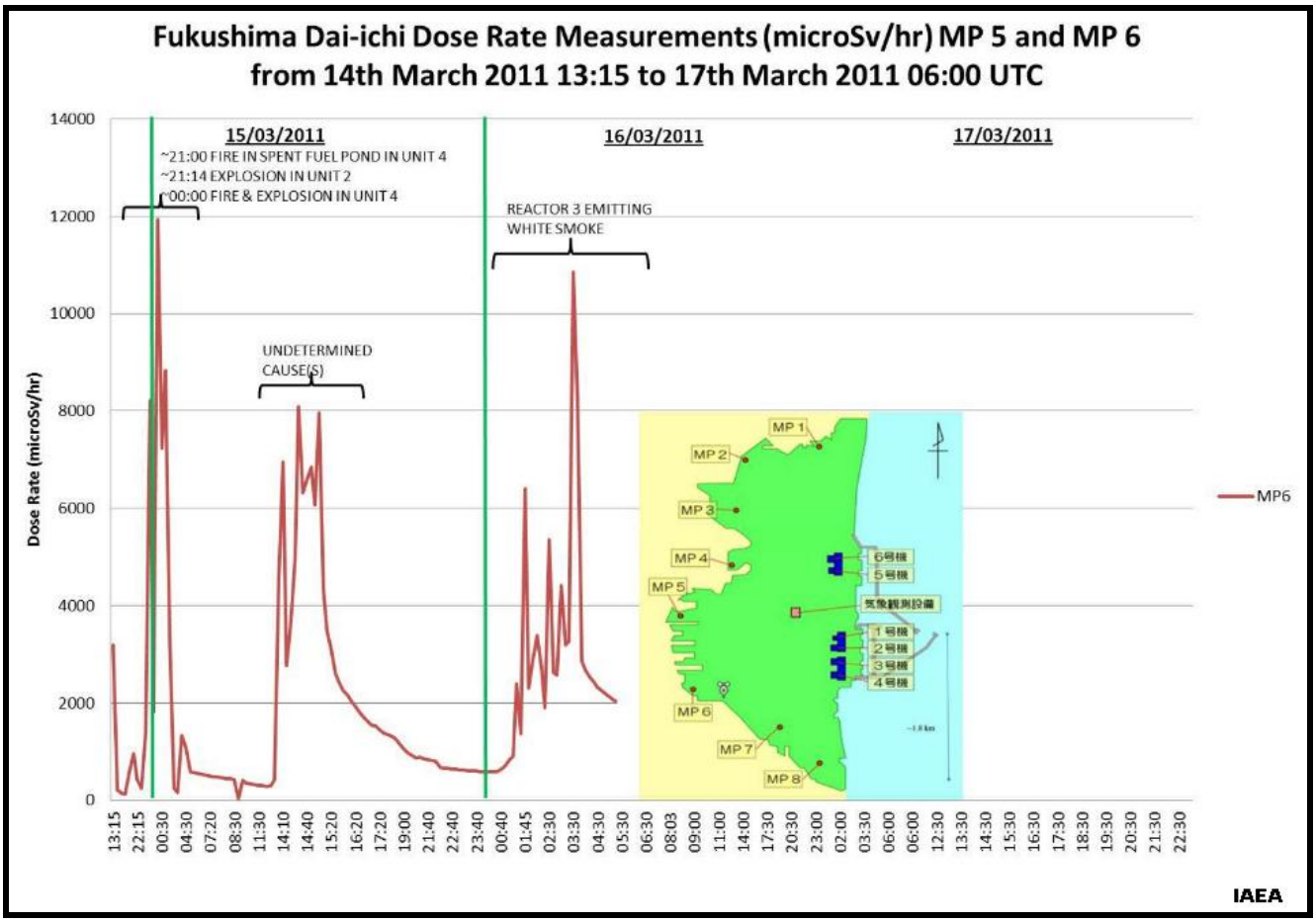


Figure 4. IAEA graph showing high radiation dose rates at Fukushima on March 15 and 16, the days with the highest monitored releases. Time is given in UCT, which is nine hours earlier than local Japanese time.

March 16

05:45 - Fire in **unit 4**, which extinguished itself within 30 minutes. Another fire may have occurred later that day.

wind direction from: northwest, changing to west
radiation level: 884.0 µSv/h at main gate

Workers are briefly evacuated due to the fire.

09:35 - Steam seen venting out of the side of **unit 2** building. Workers apparently removed panel from side of building to relieve pressure. Steam also seen rising from damaged **unit 3** building. Damage to **unit 4** building can be seen as well

wind direction from: west, changing to north-northwest
radiation level: 641.8 µSv/h at main gate

18:00 - Steam or smoke seen venting out of south-east corner of damaged unit 4 building. This spent fuel pool is located in this corner of the building in this reactor building design. Steam or smoke seen rising from damaged **unit 3** building

wind direction from: west
*radiation level: 1,591.1 µSv/h at main gate**

*Reading at 15:00. No readings later that evening.

Figure 5. Satellite image taken at 9:35am on March 16. Plumes can be seen venting out of reactor buildings 2 and 3.

Figure 6. A still image from a video shot from a helicopter showing the southeast corner of the unit 4 building at approximately 6:00pm. A plume of smoke or steam can be seen rising from the building.

Figure 7. March 16th image showing unit building 3 in the foreground with a rising plume, and a unit 4 building in the distance. (TEPCO/AFP/Getty Images)

Notable Radiation Changes on March 16

TIME	RADIATION LEVEL	MONITORING STATION	WIND DIRECTION
00:00	4251.0 µSv/h	Main Gate	North-Northeast
01:40	1708.0 µSv/h	Main Gate	Northwest
03:30	1159.0 µSv/h	Main Gate	Northwest
09:10	582.2 µSv/h	Main Gate	North
10:00	810.3 µSv/h	Main Gate	East-Northeast
10:10	908.5 µSv/h	Main Gate	Northeast
10:20	2399.0 µSv/h	Main Gate	East-Northeast
10:45	6400.0 µSv/h	Main Gate	East-Northeast
11:00	3391.0 µSv/h	Main Gate	Northeast
11:20	1900.0 µSv/h	Main Gate	East-Northeast
11:30	5350.0 µSv/h	Main Gate	Northeast
12:00	4418.0 µSv/h	Main Gate	East-Southeast
12:10	3138.0 µSv/h	Main Gate	East
12:20	3261.0 µSv/h	Main Gate	North
12:30	10850.0 µSv/h	Main Gate	East-Northeast
13:20	2430.0 µSv/h	Main Gate	West-Southwest
15:50	1591.0 µSv/h	Main Gate	West

Observations

The dose rates at the main gate decreased during the overnight, even though the winds came from the north, northeast and blew releases toward the main gate. This could imply that the releases from the reactors decreased overnight.

Another major release appears to have occurred in the late morning. The spike in dose rate at 12:30pm at the main gate is preceded by winds out of the north, east, and east-northeast, in the previous 30 minutes. As the main gate is approximately a kilometer west-southwest of the four reactors, the winds carried a release that likely occurred between 12:10pm and 12:30pm towards the main gate. However, it is unclear from which reactor building this release originated. As noted above, fires were occurring in reactor 4 and plumes can be seen rising from both buildings 2 and 4 in satellite imagery taken at 9:35 am.

March 17

10:55 - Steam can be seen venting from the top of **unit 3** building. Steam can be seen venting out of the side **unit 2** building.

wind direction from: southwest changing to northwest
radiation level: 3,753 μSv/h at north of main building
647.3 μSv/h at main gate

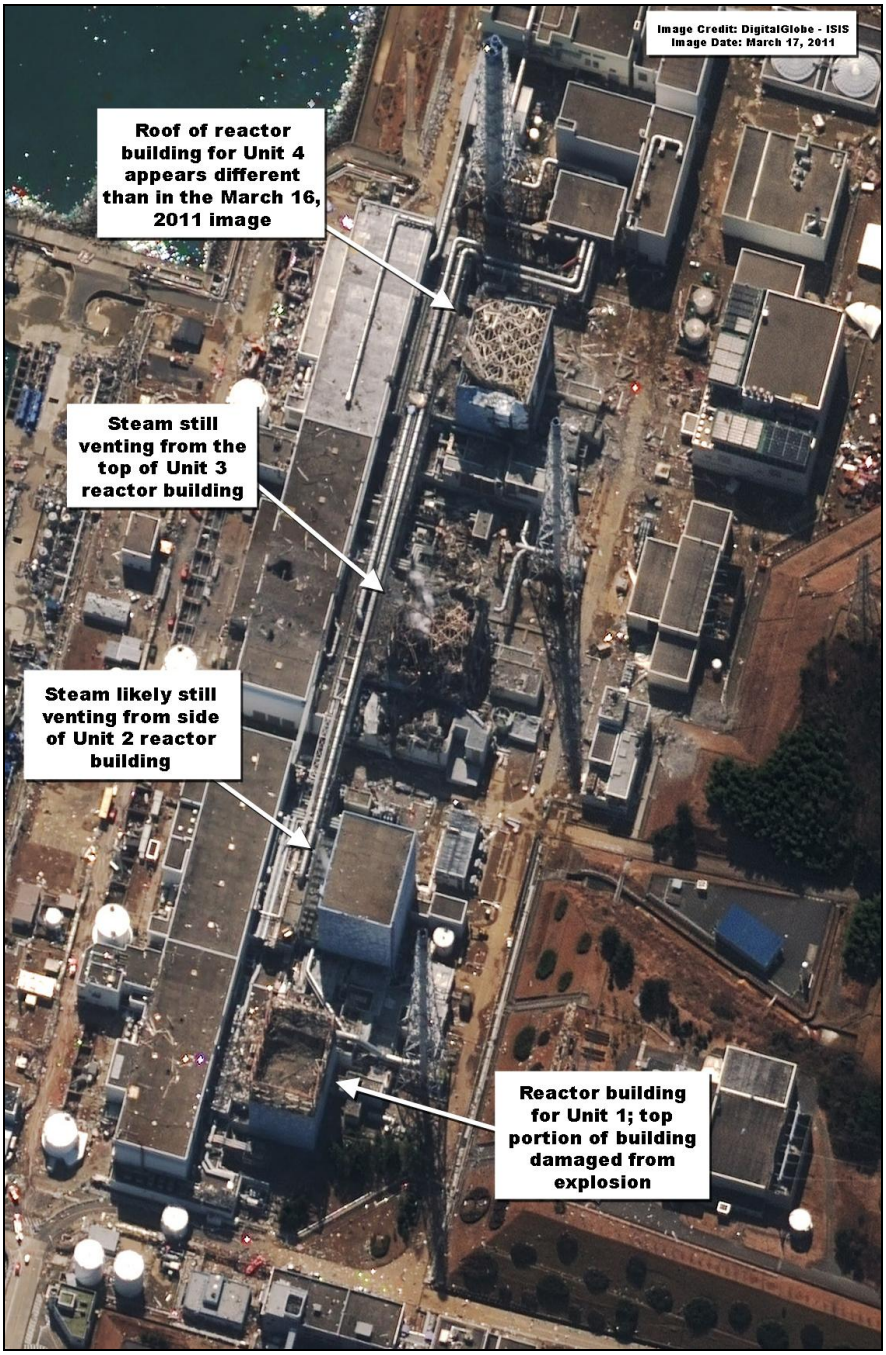


Figure 8. Satellite image from 10:55am on March 17. Steam can be seen venting from the top of unit 3 building.

Notable Radiation Changes on March 17

TIME	RADIATION LEVEL	MONITORING STATION	WIND DIRECTION
00:30	351.4 µSv/h	West Gate	Northeast
07:50	381.3 µSv/h	Side of Gym	West
09:30	3786.0 µSv/h	North of Main Building	West

Observations

The readings on the 17th were taken closer to the reactors, although the three monitoring locations are all west and north of the reactors. The reason is not given for this choice. Because of this, it is possible that the releases to the south occurred and were not detected. Because the monitoring stations for this day are closer to the plants, it is also possible that they were more affected by ground shine. Thus, the radiation detected may not have originated from separate releases, but from releases that already had deposited on the ground.

March 18

10:19 - Steam can be seen venting out of **unit 2** building. Steam is no longer visible rising from **unit 3** building. The IAEA labeled a "possible vapor plume" coming from same corner of unit 4 building

wind direction from: west changing to northwest
radiation level: 266.1 μSv/h at west gate

Figure 9. Satellite image from 10:20am on March 18.

Figure 10. A satellite image taken on 10:19am on March 18th from an IAEA presentation. The IAEA observes a "possible vapor plume" on the southeast corner of the unit 4 building.

Notable Radiation Changes on March 18

TIME	RADIATION LEVEL	MONITORING STATION	WIND DIRECTION
13:50	3484.0 µSv/h	North of Main Building	East-Southeast
15:50	4396.0 µSv/h	North of Main Building	South-Southeast
16:40	4277.0	North of Main Building	East
16:50	4735.0	North of Main Building	South-Southeast
17:00	5055.0 µSv/h	North of Main Building	South
20:00	3611.0 µSv/h	North of Main Building	West-Southwest
23:50	3244.0 µSv/h	North of Main Building	West-Northwest
00:00	287.0 µSv/h	West Gate	West
19:50	Wind data from different monitoring station	North of Main Building	West-Southwest
20:00	Wind data from different monitoring station	North of Main Building	West-Southwest
20:10	447.6 µSv/h	West Gate	South
23:20	368.9 µSv/h	West Gate	West-Northwest

Observations

The dose levels appear to be the similar to the previous day. The monitoring is still incomplete, so it is possible that releases did not intersect monitoring locations.

March 19-25

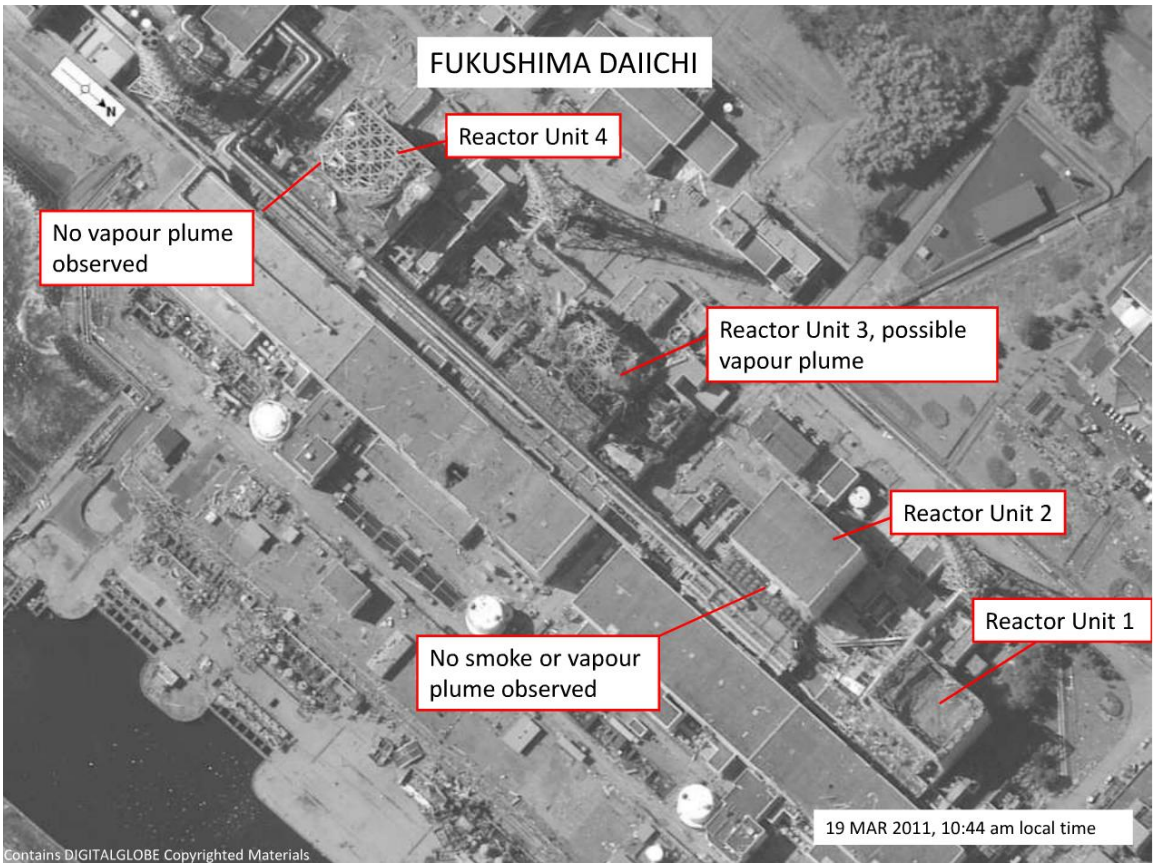


Figure 11. Satellite image taken at 11:44am on March 19 from an IAEA presentation. The IAEA does not observe a plume at the unit 4 building or unit 2 building. The IAEA does observe a possible plume above unit 3 building.

Figure 12. TEPCO/Reuters photograph from March 21 showing smoke rising from unit 3 building.

Figure 13. Still from RT News video from March 22, 2011 showing what the Federation of Electric Power Companies of Japan describes as a concrete pumping machine pumping water into the spent fuel pool in the unit 4 building. In the video, see here, a plume of either steam or smoke can be seen rising from the building.

Notable Radiation Changes on March 19 – 25

DATE	TIME	RADIATION LEVEL	MONITORING STATION	WIND DIRECTION
03/19	00:00	3329.0 µSv/h	North of Main Building	West-Southwest
	11:40	3954.0 µSv/h	North of Main Building	West-Northwest
	14:50	3340.0 µSv/h	North of Main Building	Southeast
	18:40	2292.0 µSv/h	North of Main Building	West
	02:00	313.7 µSv/h	West Gate	North
	07:50	287.2 µSv/h	West Gate	Southeast
	08:00	399.0 µSv/h	West Gate	North-Northeast
	08:10	830.8 µSv/h	West Gate	West-Northwest
	08:30	431.9 µSv/h	West Gate	East
	08:50	522.5 µSv/h	West Gate	East-Northeast
	09:30	425.2 µSv/h	West Gate	East
	11:30	313.1 µSv/h	West Gate	Southwest
03/20	00:00	2821.0 µSv/h	North of Main Building	Southwest
	03:50	3185.0 µSv/h	North of Main Building	South
	04:20	2743.0 µSv/h	North of Main Building	South
	09:00	2614.0 µSv/h	North of Main Building	East
	14:10	2923.0 µSv/h	North of Main Building	Southeast
	14:20	2923.0 µSv/h	North of Main Building	Southeast
	14:50	3346.0 µSv/h	North of Main Building	South
	15:40	3003.0 µSv/h	North of Main Building	South
	16:40	2830.0 µSv/h	North of Main Building	South-Southwest
	18:20	2673.0 µSv/h	North of Main Building	South
	23:50	2453.0 µSv/h	North of Main Building	West
	04:40	273.2 µSv/h	West Gate	North-Northwest
03/21	00:00	2452.0 µSv/h	North of Main Building	West
	16:30	2015.0 µSv/h	North of Main Building	Northeast
	16:42	1140.0 µSv/h	Main Gate	East
	16:50	508.0 µSv/h	Main Gate	South
	17:30	729.0 µSv/h	Main Gate	East
	17:40	494.3 µSv/h	Main Gate	Southeast
	17:50	1383.0 µSv/h	Main Gate	East-Southeast
	18:00	1757.0 µSv/h	Main Gate	East-Northeast
	18:30	1932.0 µSv/h	Main Gate	Southeast
	19:00	1201.0 µSv/h	Main Gate	West
	19:50	496.2 µSv/h	Main Gate	West-Northwest
	21:00	417.1 µSv/h	Main Gate	West

03/22	00:00	331.8 μSv/h	Main Gate	Southeast
	13:50	254.5 μSv/h	Main Gate	North
	19:10	363.0 μSv/h	Main Gate	Southwest
	19:20	320.0 μSv/h	Main Gate	West-Southwest
	19:30	472.7 μSv/h	Main Gate	Southwest
	23:00	235.9 μSv/h	Main Gate	West
03/23	00:00	233.4 μSv/h	Main Gate	Northwest
	14:00	222.4 μSv/h	Main Gate	North
	14:10	231.1 μSv/h	Main Gate	Northeast
	14:20	435.0 μSv/h	Main Gate	East-Southeast
	15:10	396.0 μSv/h	Main Gate	North
	15:20	415.6 μSv/h	Main Gate	East
	15:30	414.7 μSv/h	Main Gate	South-Southeast
	15:40	401.6 μSv/h	Main Gate	East-Southeast
	16:20	280.9 μSv/h	Main Gate	Southeast
	18:20	249.0 μSv/h	Main Gate	Northwest
	21:20	230.6 μSv/h	Main Gate	South-Southeast
	23:50	223.0 μSv/h	Main Gate	Southeast
03/24	00:00	222.3 μSv/h	Main Gate	Northwest
	23:50	199.6 μSv/h	Main Gate	Northwest
	14:20	429.5 μSv/h	Seismic-isolated building	South
03/25	00:00	199.5 μSv/h	Main Gate	Northwest
	10:00	216.2 μSv/h	Main Gate	East
	10:10	203.2 μSv/h	Main Gate	East-Northeast
	10:20	430.8 μSv/h	Main Gate	East
	10:30	540.0 μSv/h	Main Gate	East
	10:40	286.5 μSv/h	Main Gate	East-Southeast
	10:50	264.7 μSv/h	Main Gate	East-Southeast
	11:40	244.3 μSv/h	Main Gate	Southeast
	12:40	226.7 μSv/h	Main Gate	East-Southeast
	14:10	210.8 μSv/h	Main Gate	South
	16:00	197.4 μSv/h	Main Gate	South
	18:50	193.6 μSv/h	Main Gate	East-Southeast
	19:00	199.5 μSv/h	Main Gate	Southeast
	19:10	261.7 μSv/h	Main Gate	North-Northeast
	19:20	221.9 μSv/h	Main Gate	East
	20:30	228.4 μSv/h	Main Gate	Southeast
	20:40	205.9 μSv/h	Main Gate	Northeast
	20:50	239.6 μSv/h	Main Gate	Southeast
	21:00	204.9 μSv/h	Main Gate	North

Observations and General Conclusions

March 19 represents the last day when radiation levels increased significantly. Readings increase at main gate, at 5:50pm and decrease at 7:00pm. During and 30 minutes preceding the detected increase, the winds came out of the east-southeast. The release occurred sometime before 5:50 pm and the winds carried it to the northwest where the main gate, west of the reactors, detected it.

As of March 22, radiation levels had generally stabilized, although they remained on the order of 100 times higher than normal levels. Few notable increases and decreases occurred during this time, especially compared to the first few days following the earthquake and tsunami. This seems to indicate that the most significant releases likely occurred during the first days after the earthquake, and the latent radiation being detected may be at least partially affected by ground shine.

On March 23 workers were temporarily evacuated due to increased levels of radioactivity due to smoke emanating from unit 2. The cause of this fire remains unknown

As of March 25, Japanese officials encouraged citizens in a 30 km radius to leave. Citizens in a 20 km radius were earlier subject to mandatory evacuation.

Although the risk of explosions and other catastrophic releases to the atmosphere has diminished, the situation at the Fukushima reactors remains perilous. The recent large elevation in levels of radiation in water at the site highlights the remaining risk.