THE COLLECTIVE EFFECTIVE DOSE RESULTING FROM RADIATION EMITTED DURING THE FIRST WEEKS OF THE FUKUSHIMA DAIICHI NUCLEAR ACCIDENT

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The Magnitude 9.0 earthquake off Japan's Pacific Coast, which was the initiating event for accidents at four of the six reactors at the Fukushima Daiichi nuclear power plant, occurred at 14:46 local time on March 11th. At 15:41 a tsunami hit the plant and a station blackout ensued. A reconstruction of the accident progression by Areva[1] posited that the final option for cooling the reactors – the reactor core isolation pumps – failed just hours later in Unit 1 (at 16:36), failed in the early morning of March 13th in Unit 3 (at 02:44), and failed early in the afternoon of March 14th in Unit 2 (at 13:25). Radiological releases spiked beginning on March 15th and in the Areva analysis are attributed to the venting of the reactor pressure vessels, explosion in Unit 2, and – significantly – explosion and fire in Unit 4. Fuel had been discharged from the Unit 4 reactor core to the adjacent spent fuel pool on November 30, 2010, raising the possibility of a core melt "on fresh air."

The Japanese Ministry of Education, Culture, Sports, Science and Technology (MEXT) has posted hourly dose rates by prefecture[2] on its website. We do not currently know the geographic coordinates of these radiation monitoring sites. The English language versions of the hourly dose rate measurements by prefecture begin in table form at 17:00 on March 16th, and hourly dose rates are provided as charts[3] beginning at 00:00 on March 14th. We first extracted the early data from these charts point by point using image processing software, and these extracted points were subsequently normalized to tabular data beginning at 17:00 on March 15th from the MEXT Japanese language website provided to us by Professor Tadahiro Katsuta of Tokyo's Meiji University. Hourly dose rates were not provided by MEXT for Fukushima Prefecture, nor for Miyagi Prefecture to the north of the Fukushima Daiichi until after 17:00 on March 15th. We used the available hourly dose rate measurements by prefecture to calculate a collective effective dose for nine prefectures near the damaged Fukushima Daiichi plant, including Tokyo, as shown in the Figure 1 map.

[1] Alan Hanson, Stanford University Center for International Security and Cooperation (CISAC) Visiting Scholar, and Executive Vice President, Technologies and Used Fuel Management of AREVA NC Inc., March 21, 2011 CISAC Seminar: "The Nuclear Crisis in Japan," http://iis-db.stanford.edu/evnts/6615/March21_JapanSeminar.pdf.

[2] http://www.mext.go.jp/english/radioactivity_level/detail/1304080.htm.

[3] http://www.mext.go.jp/english/radioactivity_level/detail/1303986.htm.

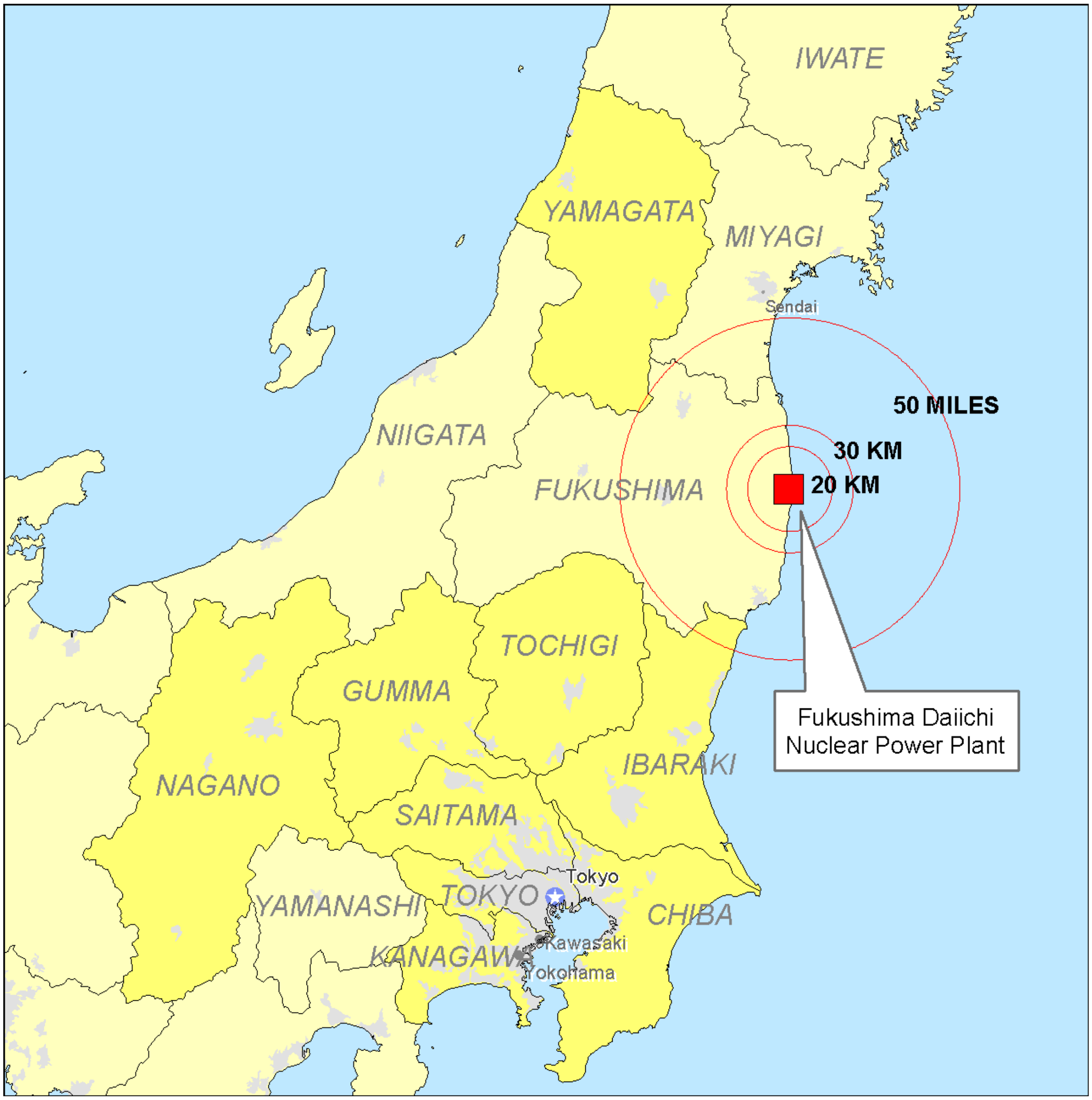

Figure 1: Hourly dose rates from MEXT for the nine prefectures highlighted in this map were used to calculate an effective collective dose over the population for radiation exposure during the first weeks of the accident. Japan prefecture (Ken and To) boundary polygon data were obtained from Harvard University.[4]

In radiation protection, the effective dose takes into account any non-uniformity of exposure and can be used to calculate the risks of cancer. The collective effective dose is the effective dose summed over the exposed population. Units of measure for collective effective dose are person-siverts, or in the older units, person-rems (1 person-rem is equal to 0.01 person-sieverts. The cancer and genetic risks for a given radiation exposure may be very small for an individual if the radiation exposure is small, but when a small exposure occurs over a large population, health effects can be expected on a statistical basis.

[4] http://www.fas.harvard.edu/~chgis/japan/datasets.html: citation for original data given as the United Nations Environment Programme (UNEP).

In Figure 2, the dose rates for Ibaraki and Tokyo prefectures are plotted by hour for a three-week time interval. Ibaraki Prefecture borders Fukuhima Prefecture, and the center of Ibaraki Prefecture is located about 130 kilometers (81 miles) southwest of the reactor accident site. Tokyo is located about 250 kilometers (155 miles) also southwest of Fukushima Daiichi. The fact that these two prefectures are in the same direction from Fukushima Daiichi, with Tokyo more distant, makes it likely that the radiation readings in Tokyo should be similar but smaller than for Ibaraki Prefecture as can be seen in Figure 2.

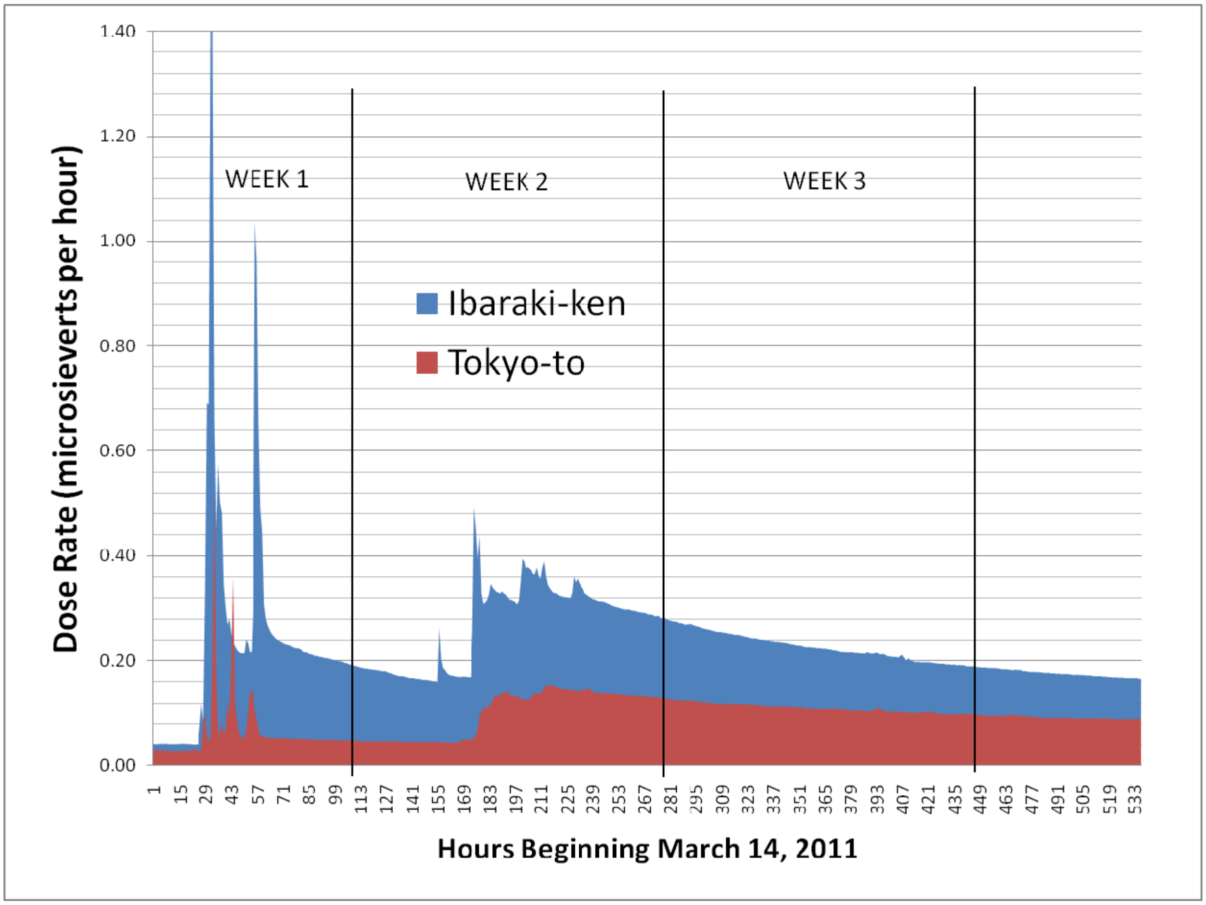

Figure 2: Hourly dose rates for Ibaraki and Tokyo Prefectures, data from MEXT.

Radiation dose rates in these nine prefectures does not just depend on proximity to the Fukushima Daiichi plant, but also depends on the prevailing winds and weather events over the course of the accident progression. Figure 3 charts the hourly dose rate in Tochigi Prefecture and Yamagata Prefecture, which both border Fukushima Prefecture. Not only is the dose rate in Yamagata lower overall than in Tochigi, but the radiation from the first prominent spikes on March 15th did not register in Yamagata Prefecture until almost a day later than it did in Ibaraki, Tochigi or Tokyo Prefectures. This disparity in dose rate depending on the direction of a prefecture from Fukushima is even more evident in Figure 4, where dose rates in Niigata Prefecture which borders Fukushima Prefecture to the west don’t appear to rise above background levels, but dose rates are higher in Kanagawa Prefecture south of Tokyo, and the radiation spikes are apparent. Figures 5 and 6 contrast the dose rates in Saitama and Chiba Prefectures, and Gumma and Nagano Prefectures, respectively.

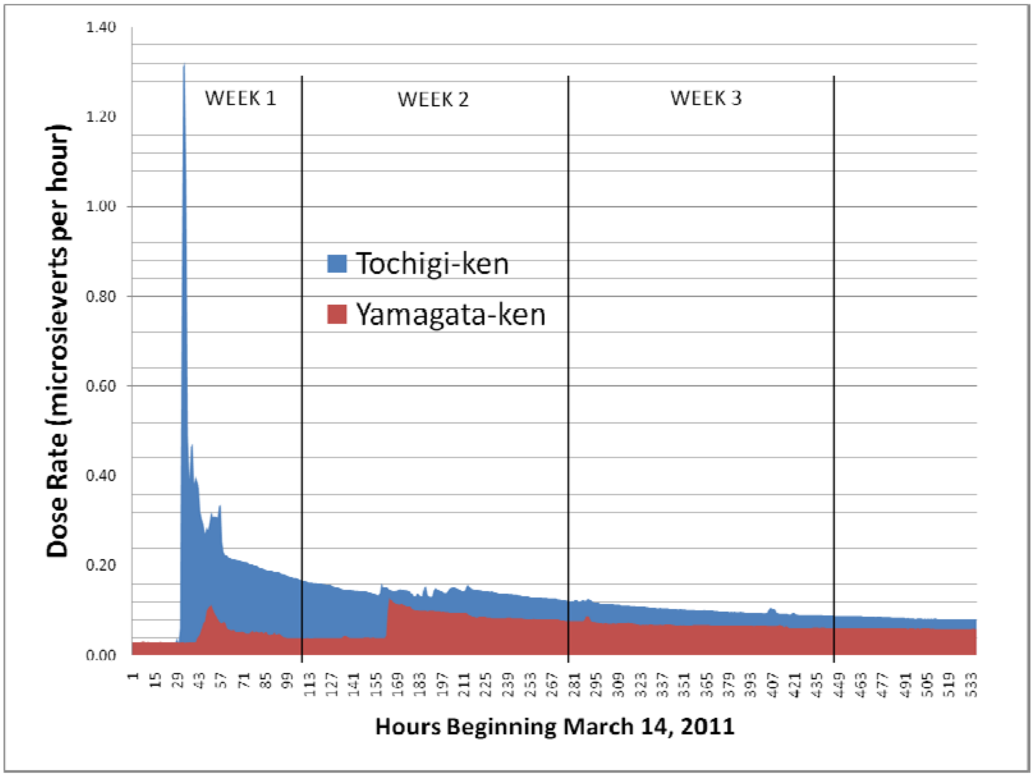

Figure 3: Hourly dose rates for Tochigi and Yamagata Prefectures, data from MEXT.

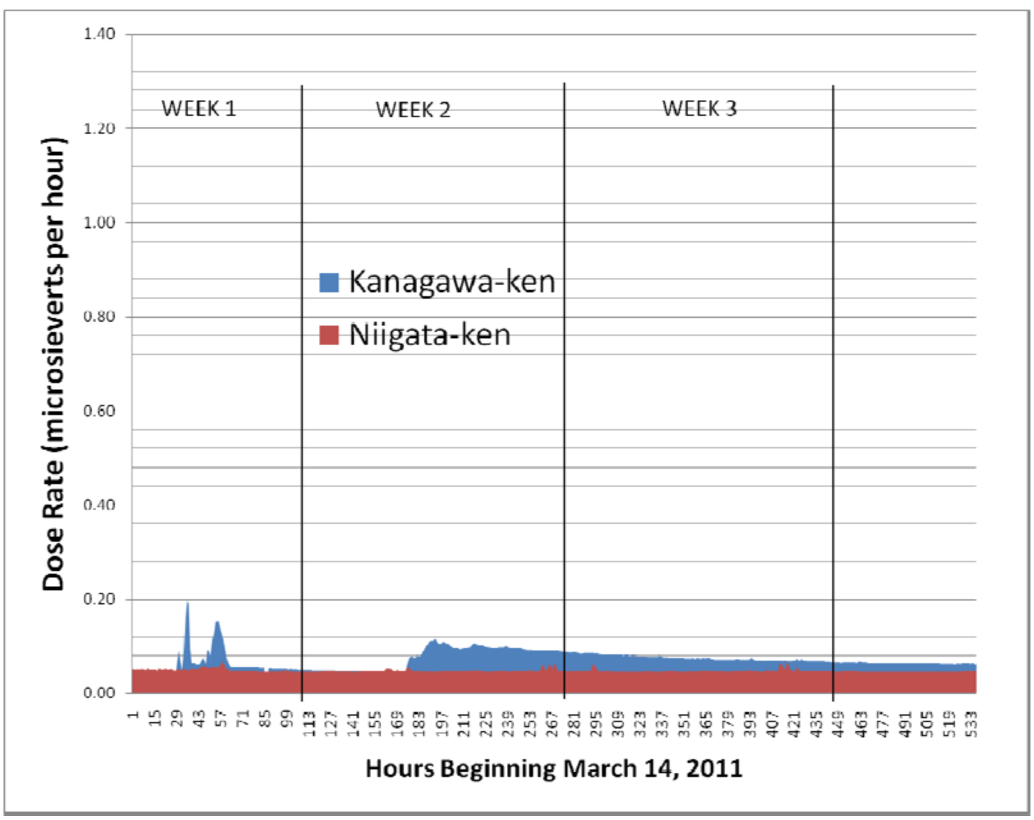

Figure 4: Hourly dose rates for Kanagawa and Niigata Prefectures, data from MEXT.

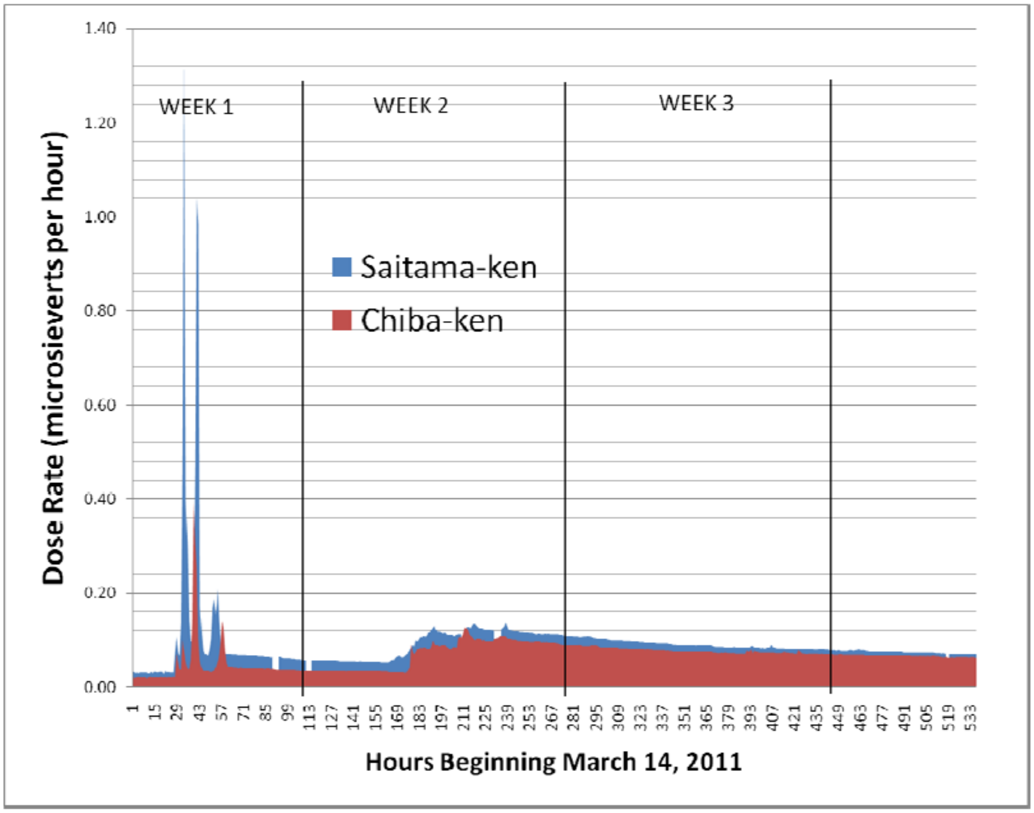

Figure 5: Hourly dose rates for Saitama and Chiba Prefectures, data from MEXT.

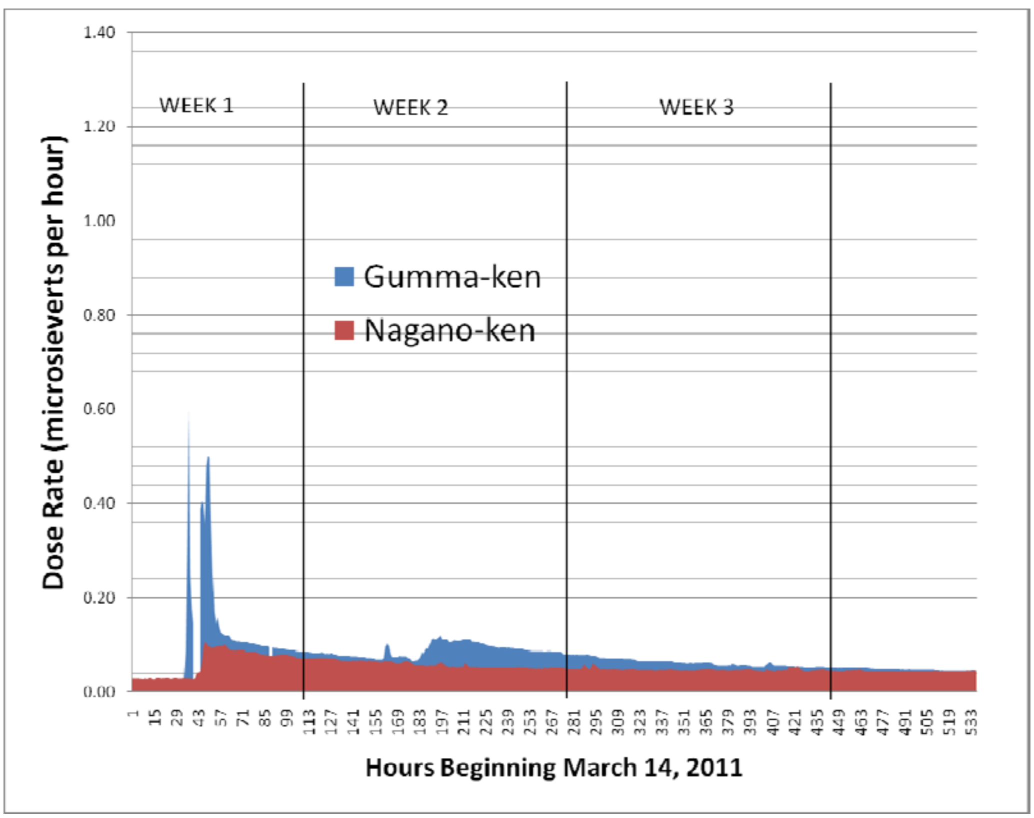

Figure 6: Hourly dose rates for Gumma and Nagano Prefectures, data from MEXT.

In order to calculate the excess collective effective dose caused by the accident, it is necessary to subtract a background radiation signal to measure health effects from the excess radiation produced by the events at Fukushima Daiichi. Ranges for background radiation levels were published by MEXT for each prefecture along with the hourly dose data, described as the "Usual Value Band." Figure 7 shows the average dose rates across eleven prefectures for March 14th and March 15th, and contrasts these dose rates with the background range provided by the Japanese government. For this analysis, we have therefore subtracted the average dose rate for March 14th as a background level in order to calculate the collective effective dose from radiation emitted during the accident.

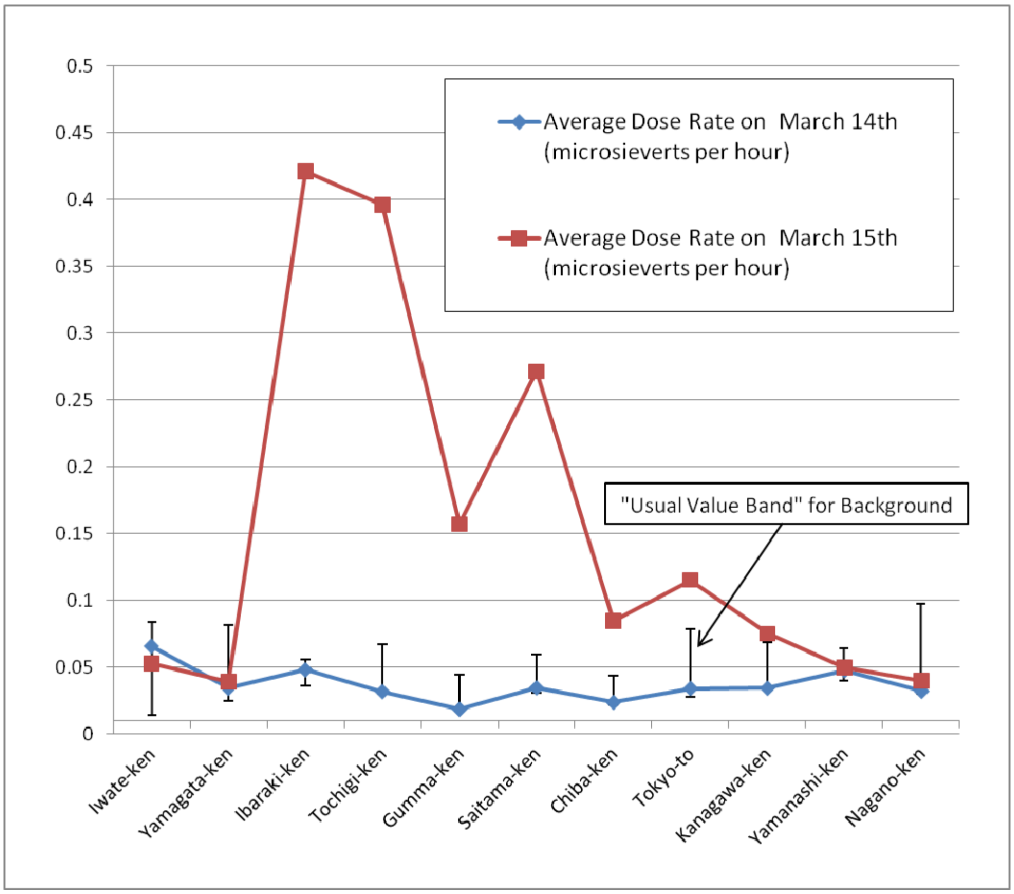

Figure 7: A chart of the average dose rate on March 14th (blue) and for March 15th (red), and the typical background ranges (black bars) for eleven Japanese prefectures near Fukushima Daiichi: all units are micro-sieverts per hour.

Hourly dose rates for the time period March 14th through April 5th were summed for nine prefectures and subtracted from background, as shown in Table 1. We obtained population data for Japan prefectures from the Japan Ministry of Internal Affairs and Communications, Statistics Bureau[5] for the year 2010. These populations were multiplied by total doses less background to calculate the collective effective dose by prefecture, as shown below in Table 2. The BIER VII Phase 2[6] best estimates were used

[5] http://www.stat.go.jp/english/data/chiri/map/index.htm.
[6] http://www.nap.edu/openbook.php?isbn=030909156X.

to estimate expected excess cancers and excess cancer deaths as a function of exposure to the radiation released from Fukushima Daiichi. These excess cases are compared with expected incidence of cancer and cancer deaths absent this exposure. The BEIR VII risk estimates are for a U.S. population of all ages. We do not have comparable risk estimates for a Japanese population, but the differences would be insignificant compared to other uncertainties.

Table 1: Hourly dose rates by prefecture were integrated over approximately 533 hours of data: from March 14, 2011 until April 5, 2011. Background dose rates for each prefecture were taken as the average dose rates on March 14, 2011 and are shown in the first column of data. Fukushima-ken and Miyagi-ken were excluded because of incomplete data released so far by the Japanese government. Iwate-ken, Niigata-ken and Yamanashi-ken measurements showed only a background signal.

JAPANESE PREFECTURE	BACKGROUND DOSE RATE (REM PER HOUR)	BACKGROUND DOSE (REM)	TOTAL DOSE (REM)	TOTAL DOSE LESS BACKGROUND DOSE (REM)
Yamagata-ken	3.447E-06	1.851E-03	3.511E-02	3.325E-02
Ibaraki-ken	4.821E-06	2.589E-03	1.270E-01	1.244E-01
Tochigi-ken	3.192E-06	1.714E-03	7.279E-02	7.107E-02
Gumma-ken	1.875E-06	9.993E-04	4.170E-02	4.070E-02
Saitama-ken	3.478E-06	1.826E-03	4.825E-02	4.643E-02
Chiba-ken	2.391E-06	1.284E-03	3.585E-02	3.456E-02
Tokyo-to	3.434E-06	1.844E-03	5.092E-02	4.908E-02
Kanagawa-ken	3.447E-06	1.844E-03	3.782E-02	3.598E-02
Nagano-ken	3.218E-06	1.728E-03	2.890E-02	2.717E-02

Table 2: Census population figures, collective dose and statistical cancers and cancer deaths calculated for radiation exposure above background over nine prefectures, from March 14, 2011 until April 5, 2011.

JAPANESE PREFECTURE	2010 PREFECTURE CENSUS POPULATION	COLLECTIVE DOSE (PERSON-REM)	EXCESS CANCER CASES	CANCER CASES ABSENT EXPOSURE	EXCESS CANCER DEATHS	CANCER DEATHS ABSENT EXPOSURE
Yamagata-ken	1,168,789	1,939	2.2	489,839.5	1.1	238,666.7
Ibaraki-ken	2,968,865	30,019	34.1	1,244,251.3	17.1	606,242.2
Tochigi-ken	2,007,014	11,169	12.7	841,139.6	6.4	409,832.3
Gumma-ken	2,008,170	6,367	7.2	841,624.0	3.6	410,068.3
Saitama-ken	7,194,957	21,580	24.5	3,015,406.5	12.3	1,469,210.2
Chiba-ken	6,217,119	14,304	16.2	2,605,594.6	8.2	1,269,535.7
Tokyo-to	13,161,751	42,752	48.5	5,516,089.8	24.4	2,687,629.6
Kanagawa-ken	9,049,500	17,537	19.9	3,792,645.5	10.0	1,847,907.9
Nagano-ken	2,152,736	2,500	2.8	902,211.7	1.4	439,588.7
Total	**45,928,901**	**148,167**	**168.2**	**19,248,802**	**84.4**	**9,378,681.6**

There are several factors that make our current estimate of collective effective dose from the Fukushima accident highly uncertain. First, we did not include a sheltering factor. Staying indoors will significantly reduce a person's dose from ionizing radiation in the environment, which is the principal of the Cold War fallout shelter. Some measurements published by the Japanese government illustrate this fact. On March 16th at 8:16 AM local time, at a point 60 kilometers northwest of the Fukushima Daiichi plant, radiation readings were recorded as 18.0 micro-sieverts per hour outdoors and 1.5 micro-sieverts per hour indoors.[7] Secondly, media reports indicate that people have been voluntarily leaving Tokyo, and the earthquake and tsunami have resulted in displaced persons in some of these prefectures. The 2010 Japanese census data does not likely represent the actual populations in these prefectures during the radiation exposures.

Factors that could contribute to an increase in the collective effective dose over what we have calculated are the contributions of other radiation exposure pathways – ingestion of contaminated water and food, and inhalation of radioactive particles. And as noted above, the analysis does not include Fukushima and Miyagi Prefectures due to lack of continuous radiation monitoring data available to us at this time. Importantly the accident is still ongoing, so there will be a contribution to the collective effective dose from exposures after April 5, 2011. Finally, these calculations are for a single value of dose rate across an entire prefecture – weather, topography and other factors will likely have produced areas with greater or lesser dose rates than MEXT reported for the entire prefectures.

We may compare this value of collective effective dose with that of the Pennsylvania's 1979 Three-Mile Island partial core meltdown and the Ukraine's 1986 Chernobyl reactor explosion and fire. Given uncertainties in our estimate, we find the collective dose from external exposure to date—and consequentially excess cancers that are projected to result from this exposure pathway—appears to be roughly one to two orders of magnitude, i.e., ten to one hundred times, greater than the collective radiation dose resulting from the Three Mile Island (TMI) accident, which was on the order of 2,000 person-rem. The collective dose from the Fukushima accident appears to be in the neighborhood of two orders of magnitude less than that from the Chernobyl accident, which is estimated to have been 25.5 million person-rem[8]. In the aftermath of the accident at Fukushima Daiichi, extensive dose reconstructions will certainly be undertaken that will include better data on radiation levels, weather, other exposure pathways, and population distribution, as was done for Three-Mile Island and continues today for Chernobyl.

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[7] MEXT, "Readings at Monitoring Post out of 20 Km Zone of Fukushima Dai-ichi NPP, As of 20:00 March 16, 2011," at: http://www.mext.go.jp/component/english/__icsFiles/afieldfile/2011/03/20/1303972_1620.pdf.
[8] http://www.unscear.org/unscear/en/chernobyl.html.