Fukushima-Daiichi Nuclear Disaster

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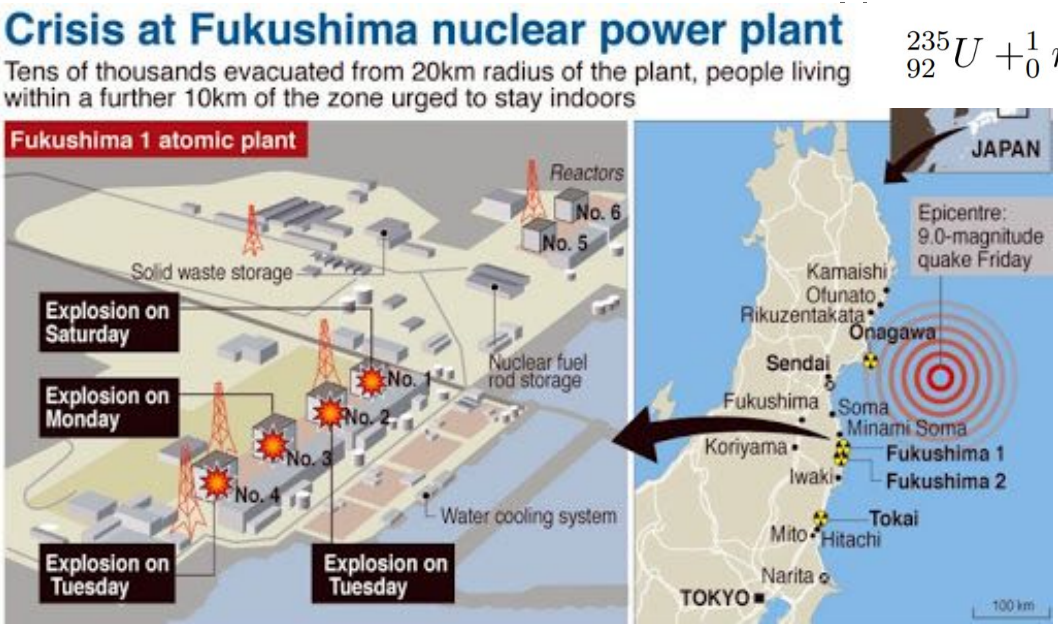
Introduction



$$^{235}_{92}U +^1_0 n \rightarrow \text{fission fragments} + \gamma + \nu_e + 193MeV$$

- Great East Japan earthquake: 11 March 2011, 2:46 pm
- SCRAM shutdown
- Tsunami destroyed emergency generators
- Overheating of cores
- Zircaloy fuel rods -> Zr oxidation: liberation of hydrogen + heat

Activity Calculations

Key radioactive isotopes:

^{131}I (8 days), ^{137}Cs (30 years),

^{134}Cs (2 years), ^{90}Sr (29 years)

$$A(t) = A_0 e^{-\lambda t} = A_0 e^{-\ln 2 (t/t_{1/2})}$$

Nuclide	Initial Activity	Half-Life
^{131}I	150 PBq	8.02 days
^{137}Cs	12 PBq	30.17 years

News Release

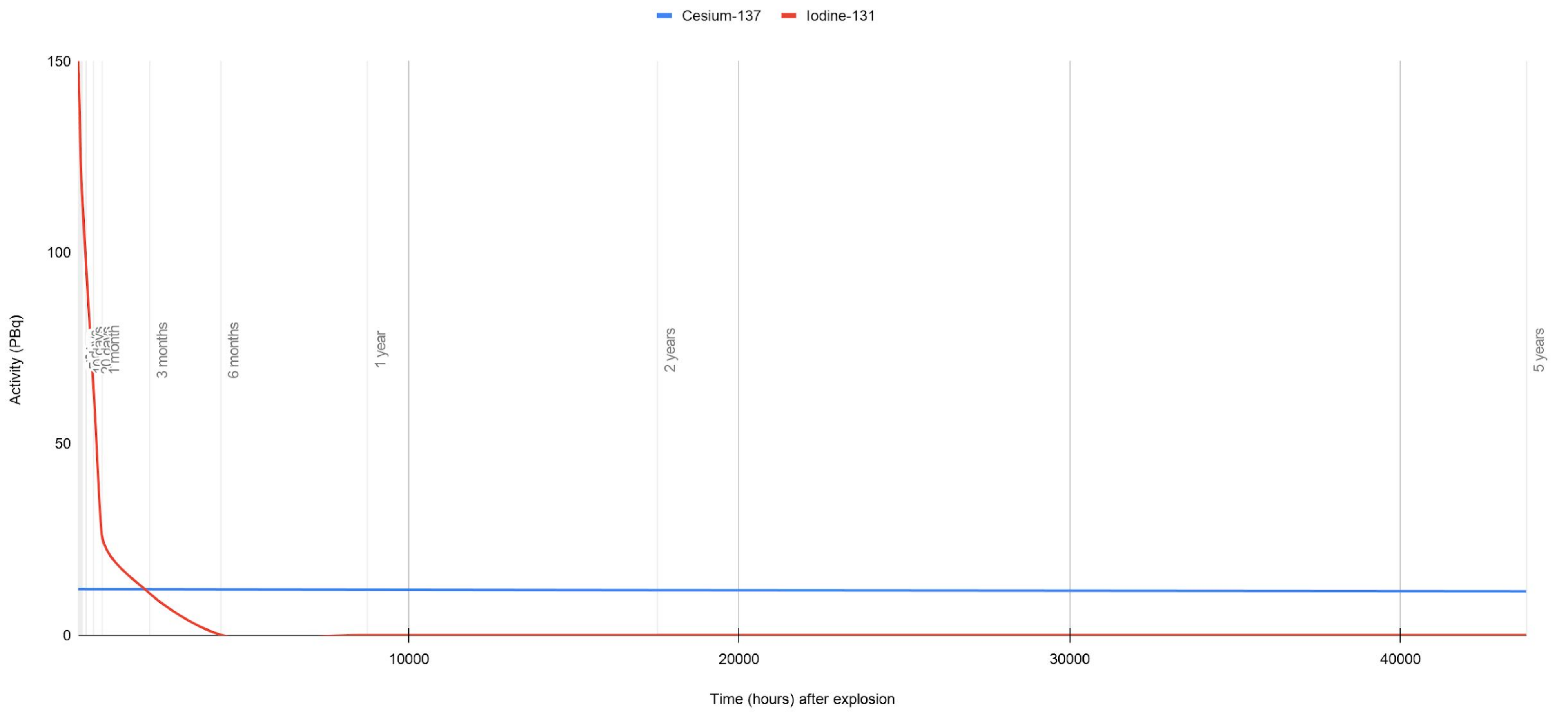
経済産業省
Ministry of Economy, Trade and Industry

April 12, 2011

INES (the International Nuclear and Radiological Event Scale) Rating on
the Events in Fukushima Dai-ichi Nuclear Power Station
by the Tohoku District - off the Pacific Ocean Earthquake

Time	Time (hours)	Cesium-137	Iodine-131
	0	12	150
2 hrs	2	11.9999371	148.9131566
4 hrs	4	11.9998742	147.834188
6 hrs	6	11.9998113	146.7630372
12 hrs	12	11.99962261	143.5959272
1 day	24	11.99924523	137.4652687
2 days	48	11.99849051	125.9780007
3 days	72	11.99773584	115.4506648
5 days	120	11.99622664	96.9616262
10 days	240	11.99245447	62.67704638
20 days	480	11.98491368	26.18941428
1 month	720	11.97737764	10.94316756
3 months	2160	11.93226078	0.05824338787
6 months	4320	11.86490394	0.0000261528154
1 year	8760	11.72763992	0
2 years	17520	11.4614615	0
5 years	43800	10.69862908	0

Calculated Activities vs Time



Theoretical Modelling of Concentration Profile

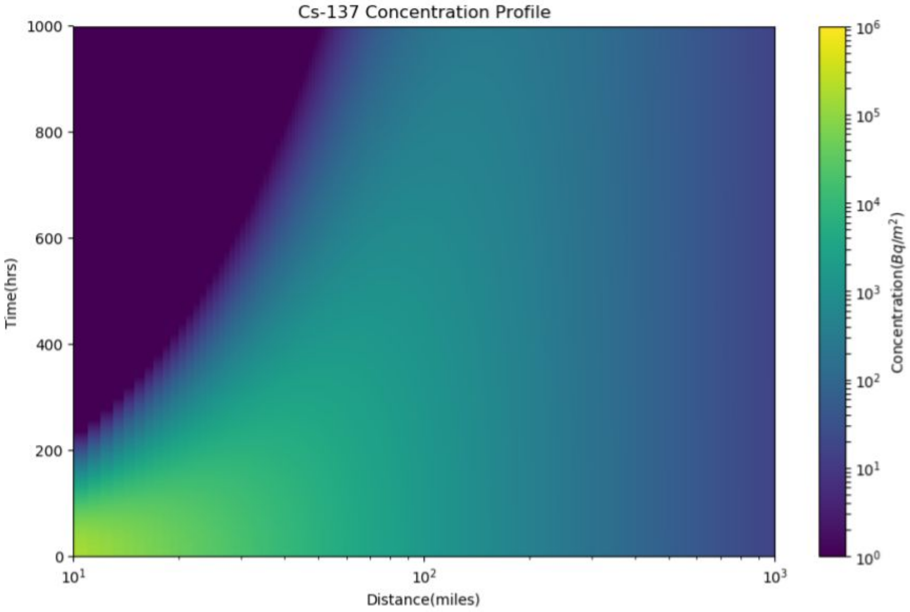
N_0: initial concentration of radioactive nuclei

λ: rate constant for that element

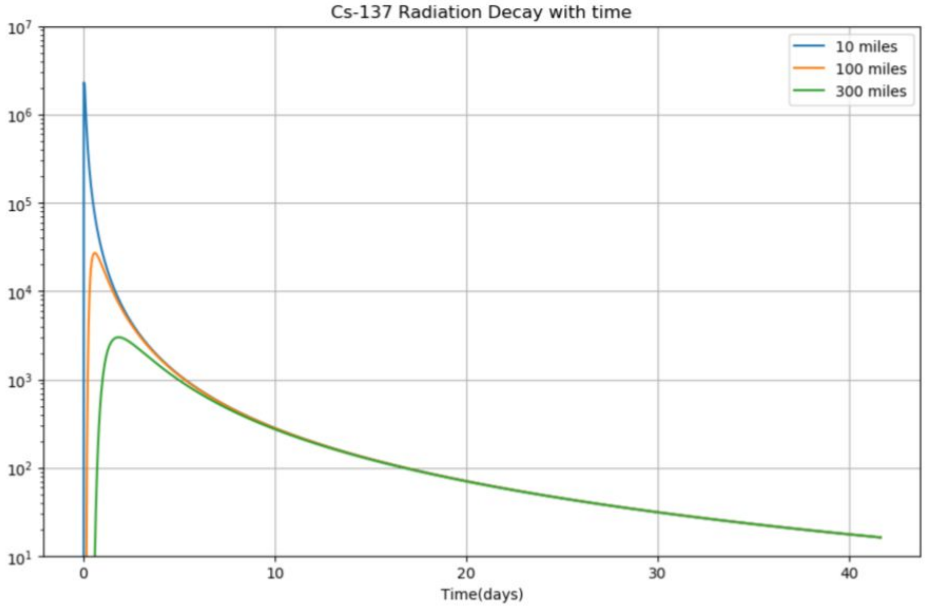
$\sigma(t) = d_0 + vt$: time-dependent standard deviation of Gaussian radial distribution
where d0 = 1 mile characterizes the initial extended source
and v the sped with which the nuclei spread (eg: if via air, then v is wind speed)

$$C = \frac{N_0 e^{-\lambda t}}{2\pi\sigma^2} e^{-\frac{r^2}{\sigma^2}} Bq/m^2$$

Cesium-137

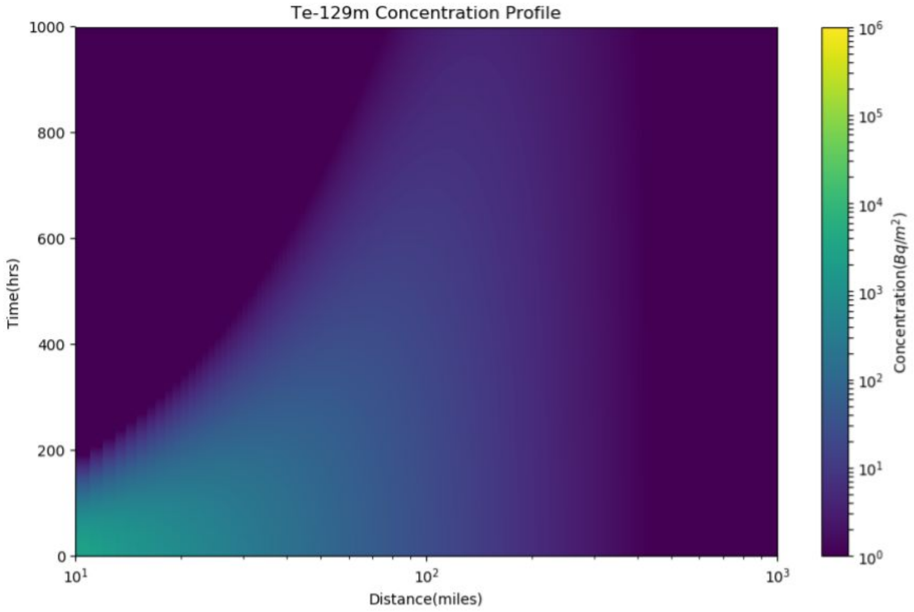


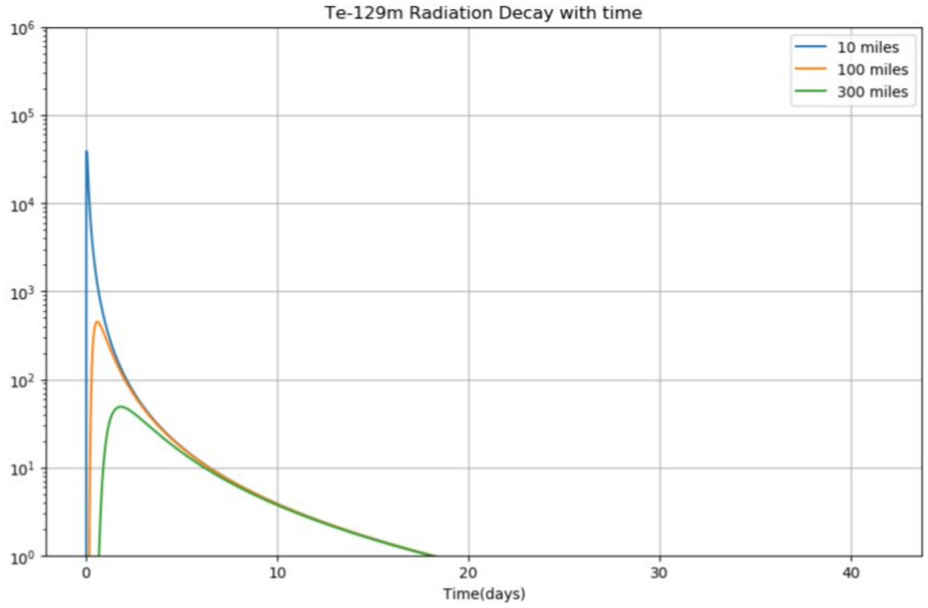
Cs-137 Concentration Profile
Time(hrs)
Distance(miles)
Concentration(Bq/m^2)
0
200
400
600
800
1000
10^1
10^2
10^3
10^0
10^1
10^2
10^3
10^4
10^5
10^6



Cs-137 Radiation Decay with time
10 miles
100 miles
300 miles
Time(days)
0
10
20
30
40
10^1
10^2
10^3
10^4
10^5
10^6
10^7

Similarly for Tellurium-129m (meta-stable isotope)





Activity Profiles: Spatial Variation

- Goal: Understand how radiation spread over various distances.

Credit:
https://wolfemouth.wordpress.com/2011/04/19/quiet-niseko-spring-snow/distance-to-fukushima-map/

Theoretical Estimate

- Simplified Model: particles travel radially out from a point source, emitting S particles per second isotropically.

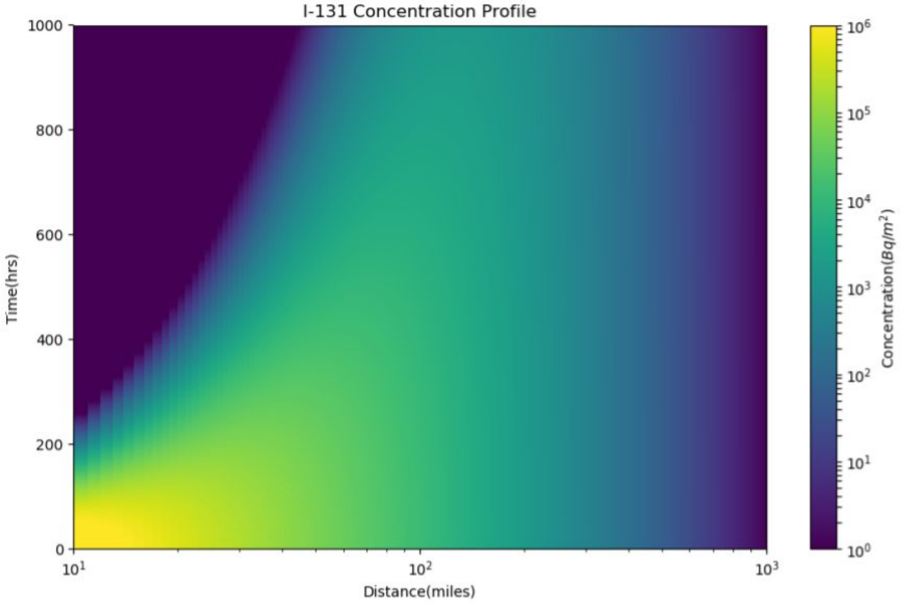
$$\Phi(r) \; = \; \frac{\alpha}{r^2}$$

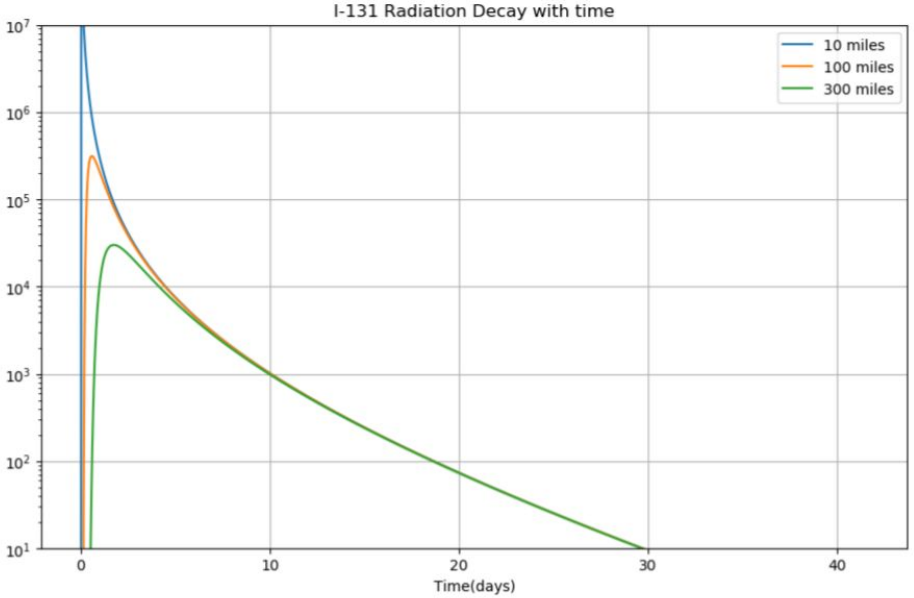
where flux is Φ and α is a constant.

- We ignore interparticle scattering (and with atmospheric particulates) - Can be included.
- Isotropic spread assumption - Not entirely true. Reasons?
- Inclusion of Scattering:

$$\Phi(r) \; = \; \alpha \cdot \frac{e^{-\beta r}}{r^2}$$

Iodine-131


I-131 Concentration Profile
Time(hrs)
1000
800
600
400
200
0
10^1
10^2
10^3
Distance(miles)
Concentration(Bq/m^2)
10^6
10^5
10^4
10^3
10^2
10^1
10^0


I-131 Radiation Decay with time
10 miles
100 miles
300 miles
10^7
10^6
10^5
10^4
10^3
10^2
10^1
0
10
20
30
40
Time(days)

Thus we expect that

Fukushima radiation

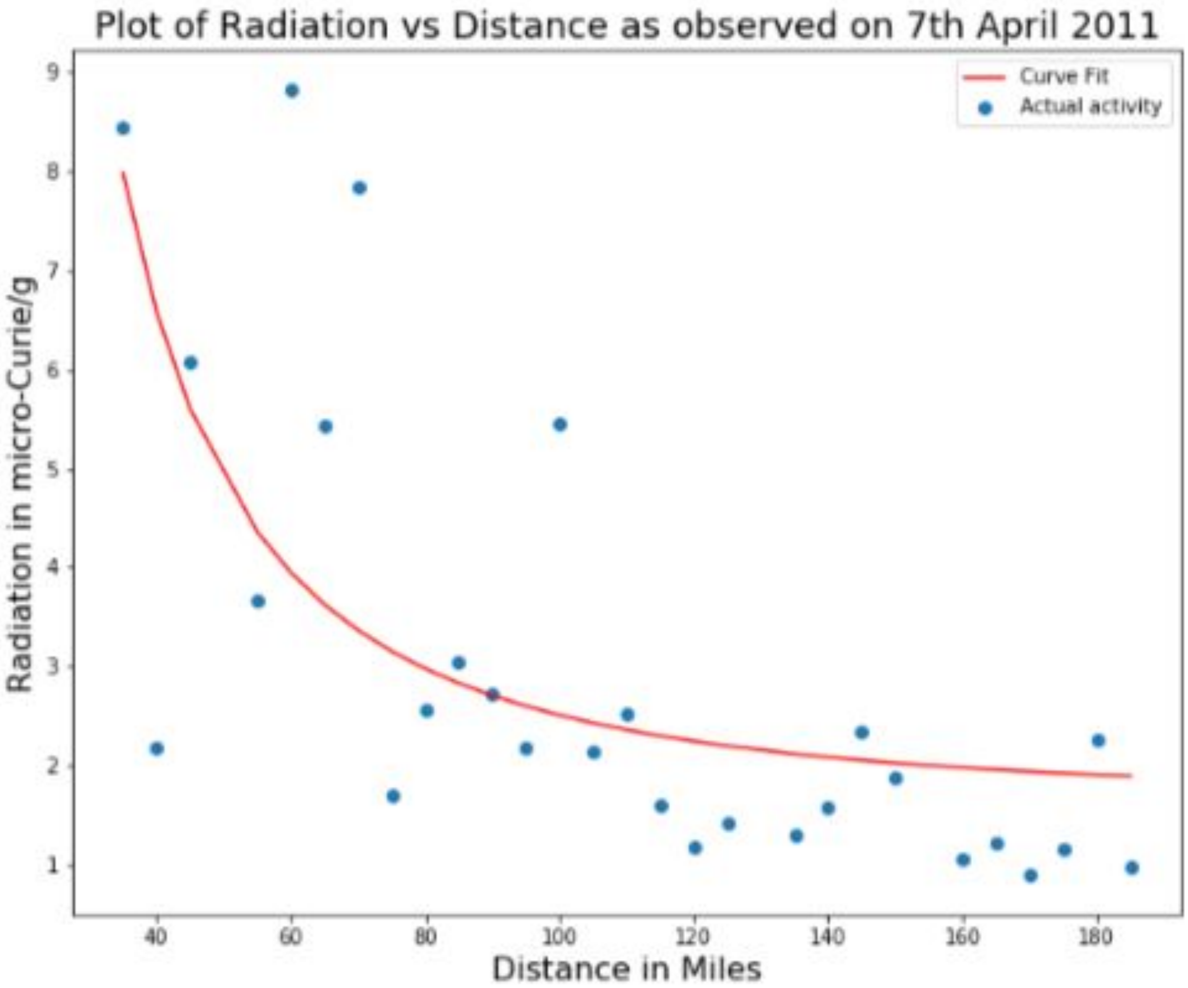
Decays faster than r^{-2}

- Reality:
  - Winds,
  - Obstructions
  - rainfall....

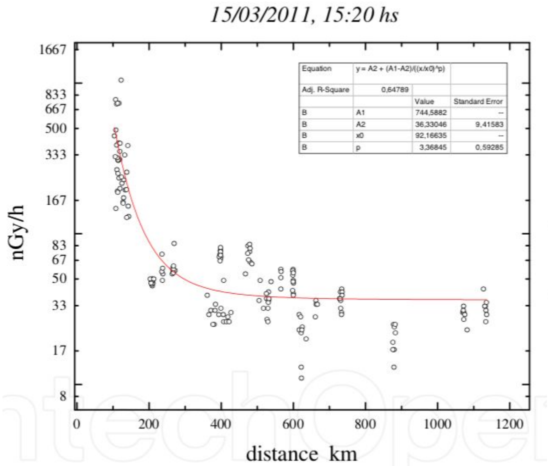
Actual Plot:

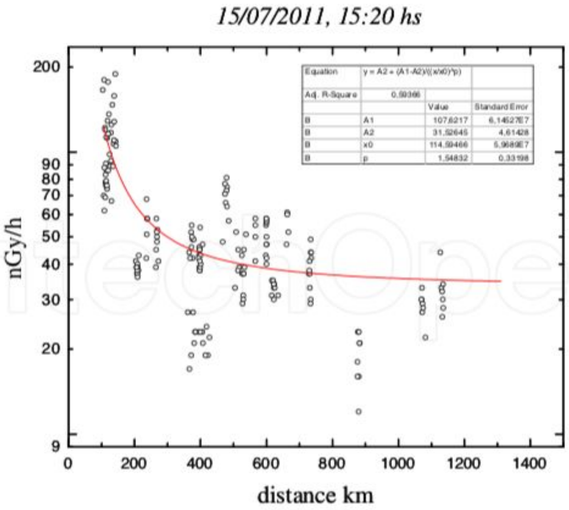
$$y = a \cdot \frac{e^{-br}}{r^2} + c$$

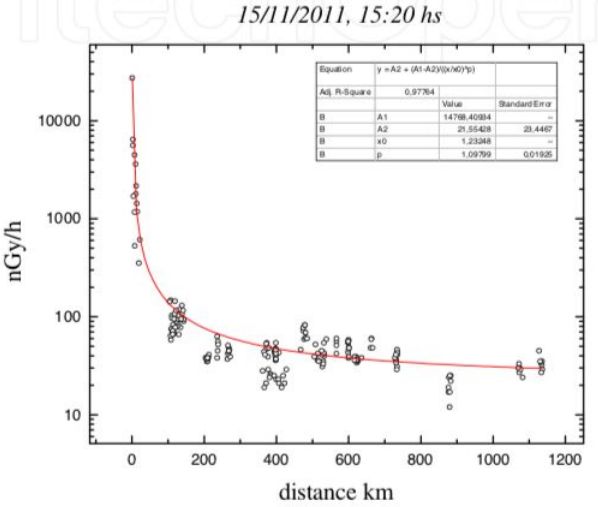
$$b = 7.0568e - 3$$



Comparison with literature







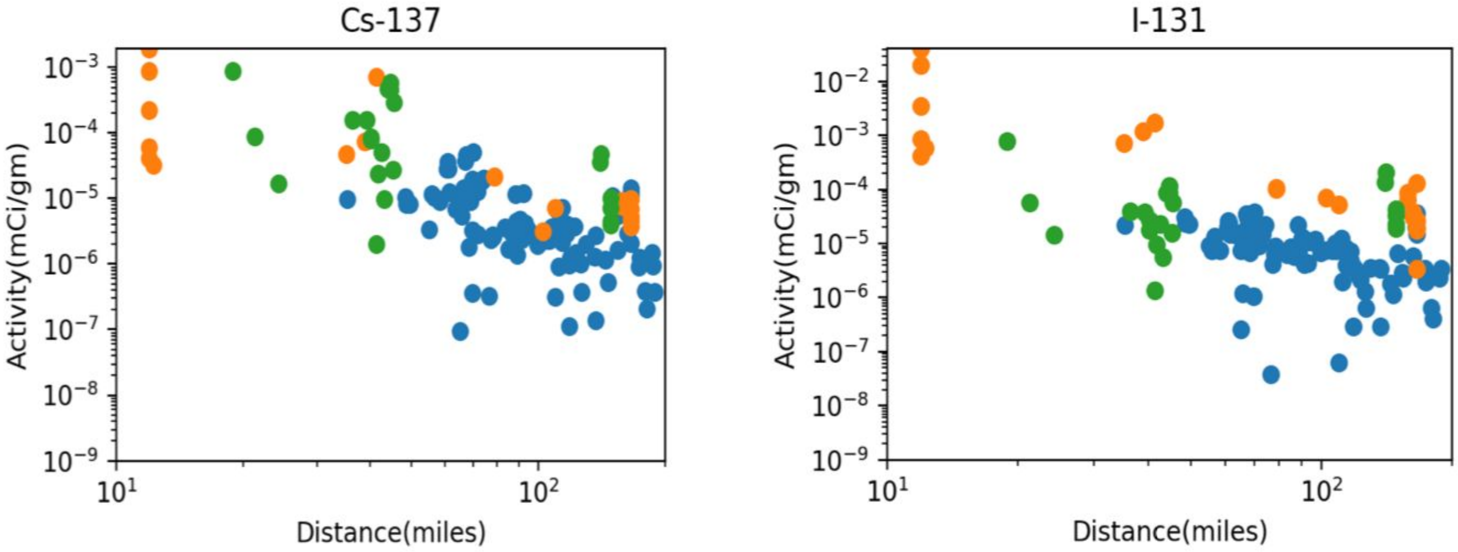
P = 3.36 (fast decay)

P = 1.5 (slow)

p=1.09

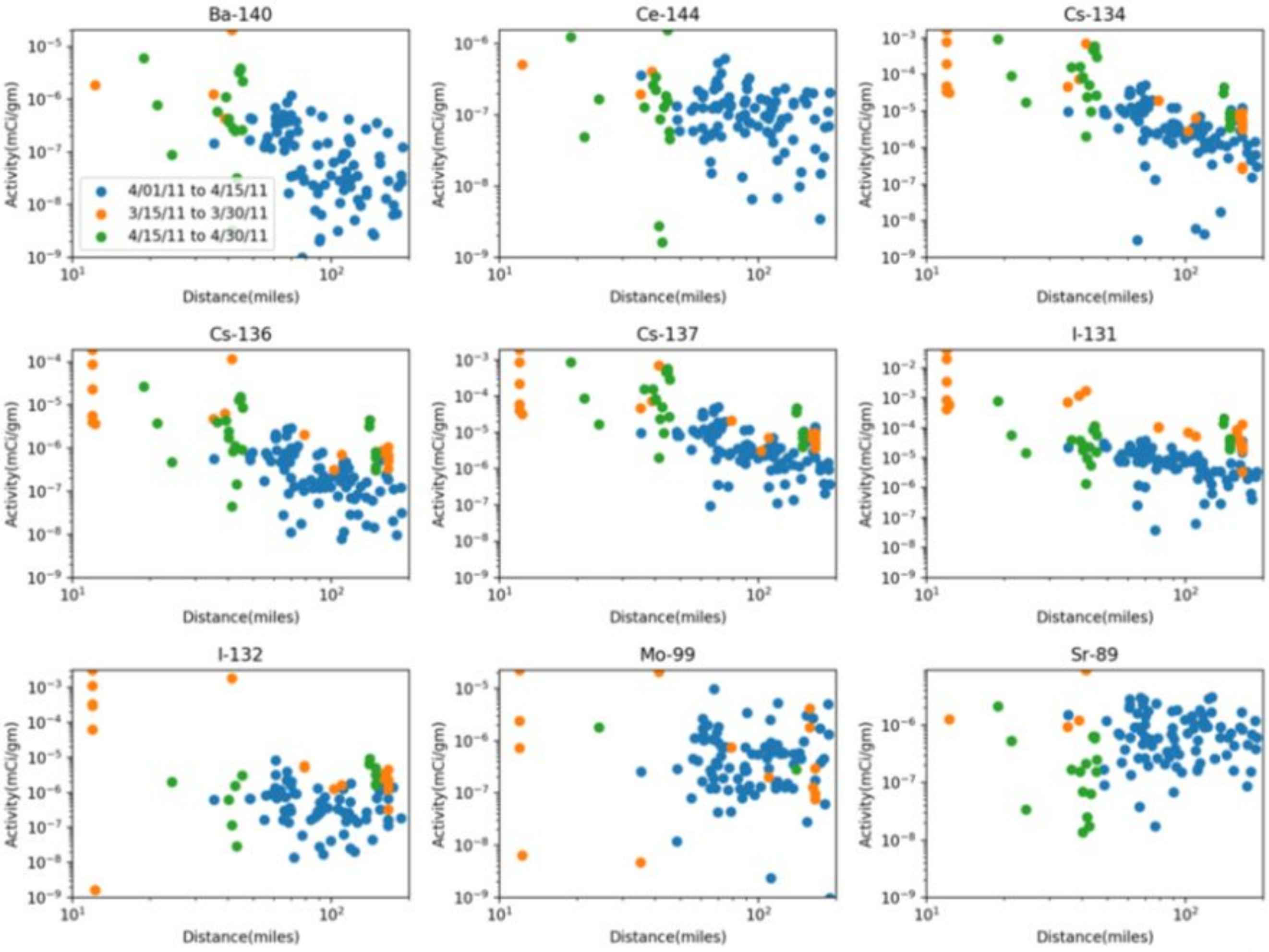
Plots of Radiation vs distance: Fit with $\frac{1}{r^p}$

Spatial Variation for elements:

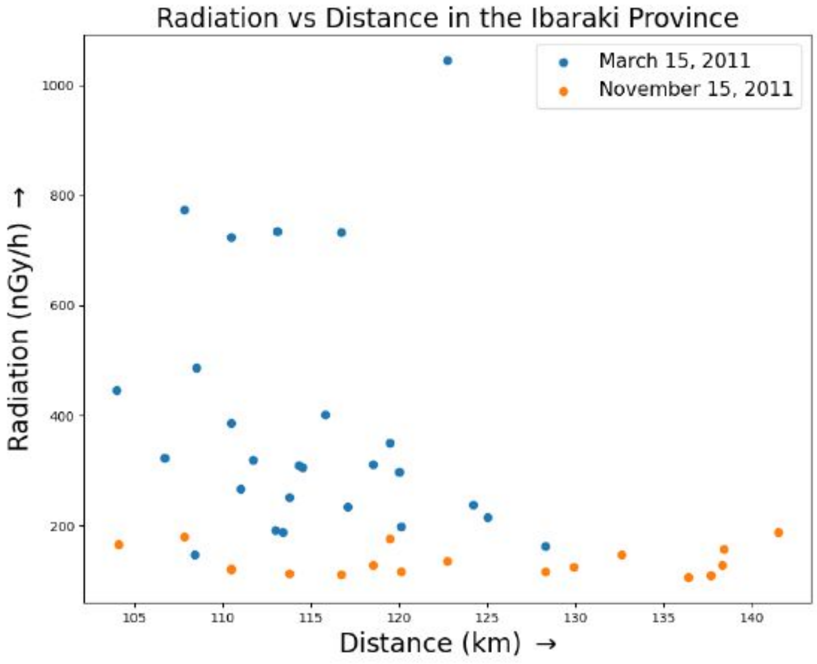


- 15/03 - 30/03
- 1/4 - 15/4
- 15/4-30/4

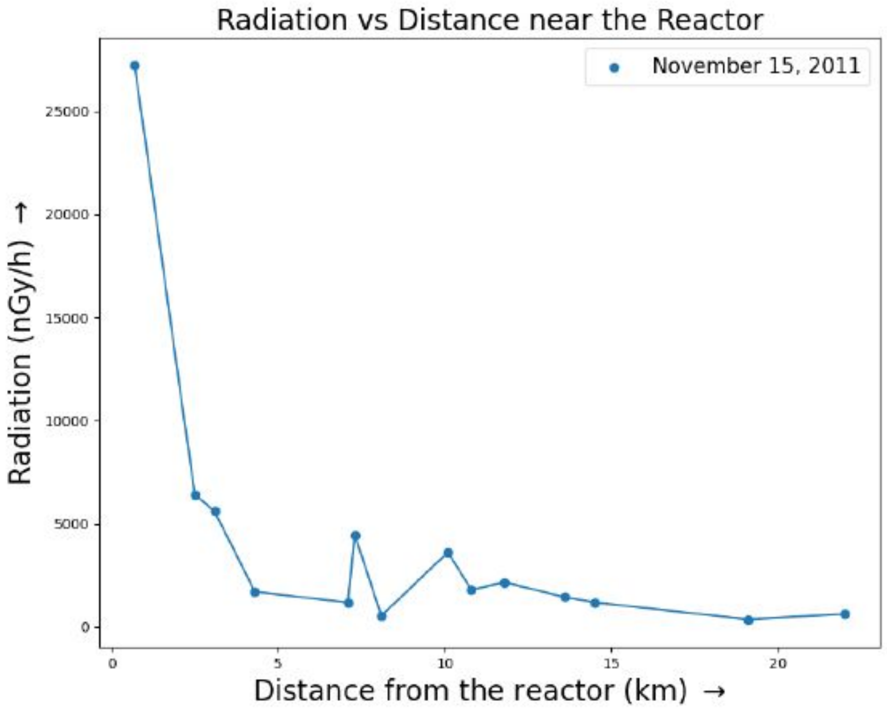
Plots of spatial Variations for many elements



Exponential Decay and Reactor Proximity



Exp decay



Steep rise

Aspects of Impact:-

A. On the General Public:
   a. Significant contributors: Radionuclides from Plume of smoke, deposition on ground, internal exposure of the thyroid gland, due to the intake of iodine-131, Cs-137 deposition
   b. Estimated dosages before and during evacuation:
      i. Adults: less than 10 mSv and about half of that level for those evacuated early on 12 March 2011.
      ii. Infants: twice that for adults, major Infant contribution is from ingesting radioactivity through food
   c. No radiation-related deaths or acute diseases were observed. A health survey (FHMS), beginning in Oct 2011, is planned to continue for 30yrs.

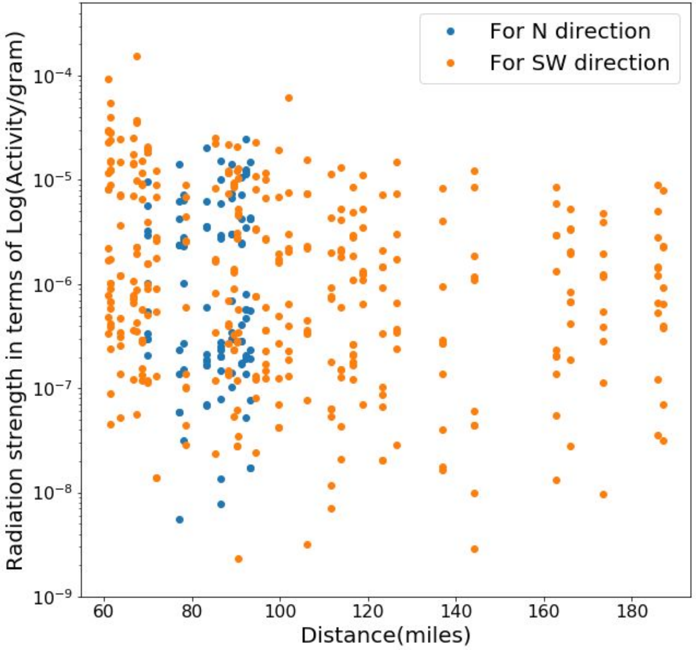
B. On Children:

- For a given radiation dose, children are generally at more risk of tumour induction(I-131).
- Data from similar screening protocols in areas not affected by the accident imply that the apparent increased rates of detection among children in Fukushima Prefecture are unrelated to radiation exposure.

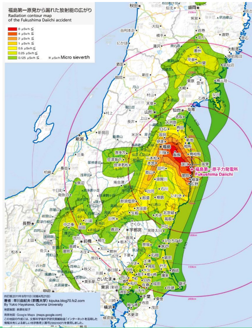
C. On Power Station Workers:

- Average effective dose : 12mSv
- Large variation - 35% of the workforce received total doses of more than 10 mSv over that period (Oct 2012), while 0.7% of the workforce received doses of more than 100 mSv.
- Mostly due to inhaling I-131.

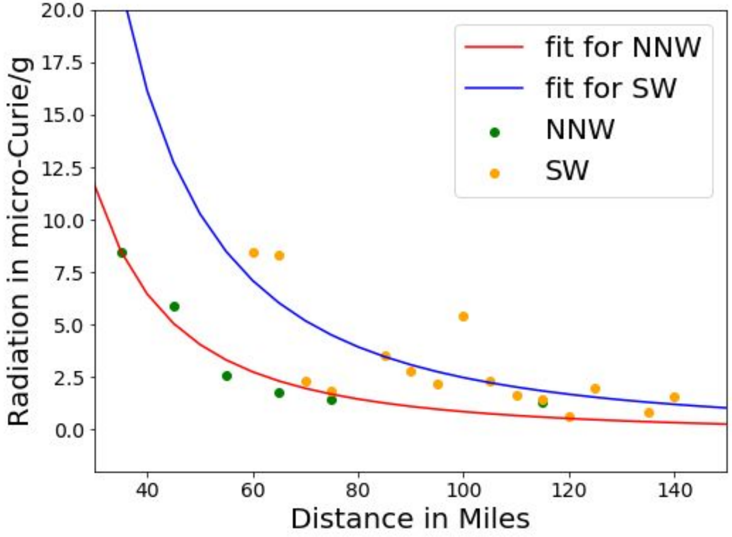
Direction dependence of radioactivity profiles

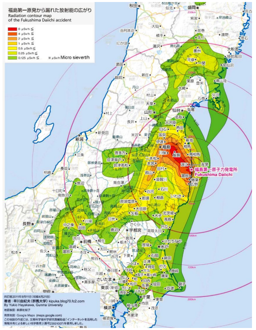


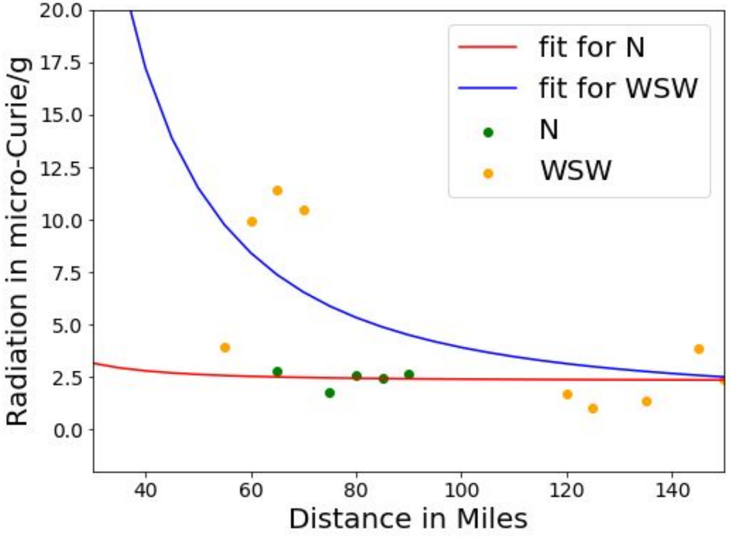
- Fukushima has uneven topography and close proximity to coastline.
- Spread is governed by geographical factors such as rainfall, water bodies, wind patterns, presence of mountains, etc.
- So, we expect some directional dependence (no radial symmetry as assumed earlier)



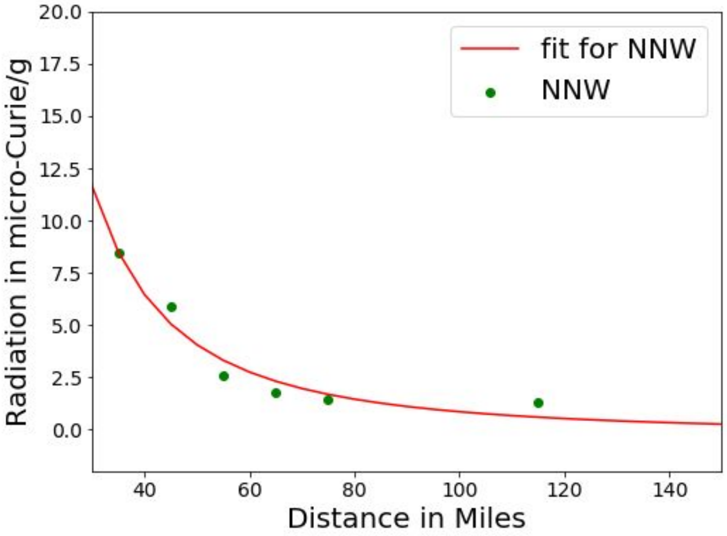
Plots for 7th April 2011 in various directions

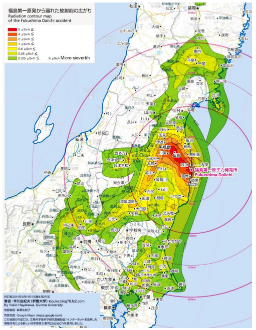


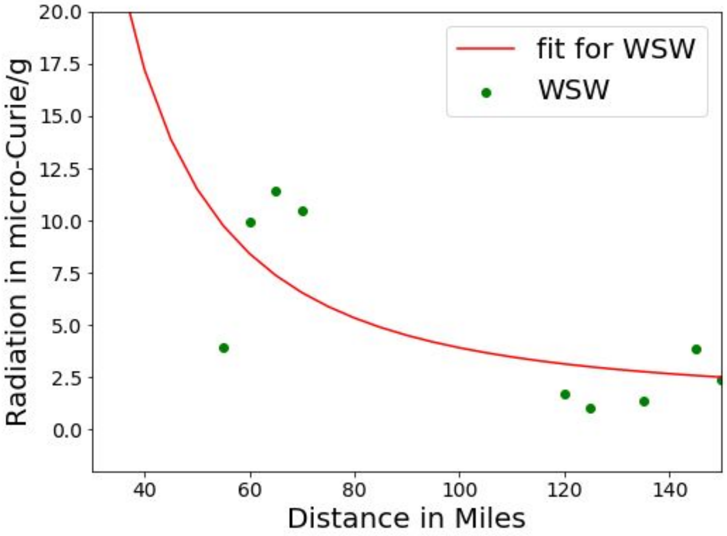




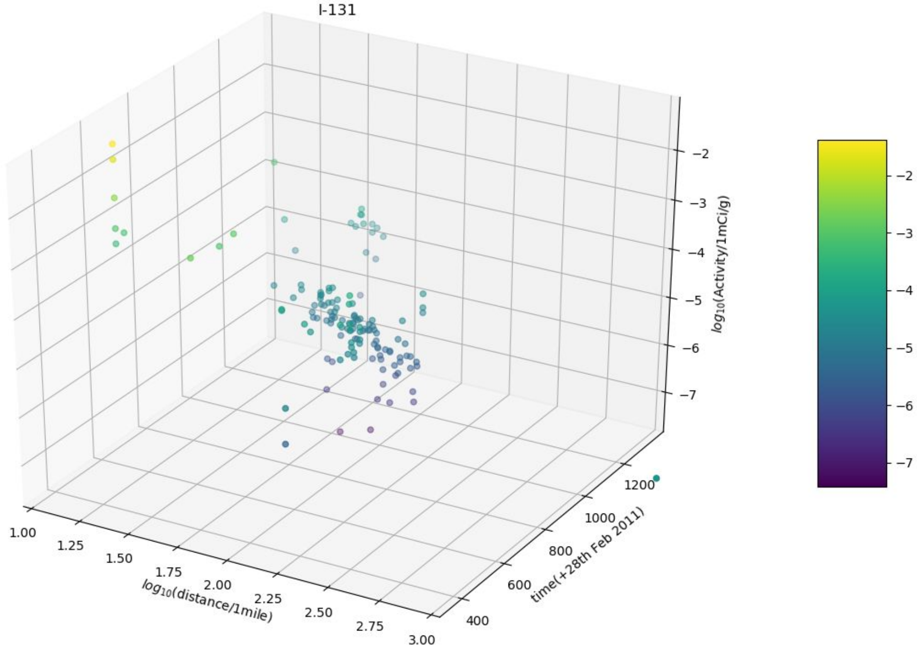
Plots for 7th April 2011 in various directions (r^{-2} fit)

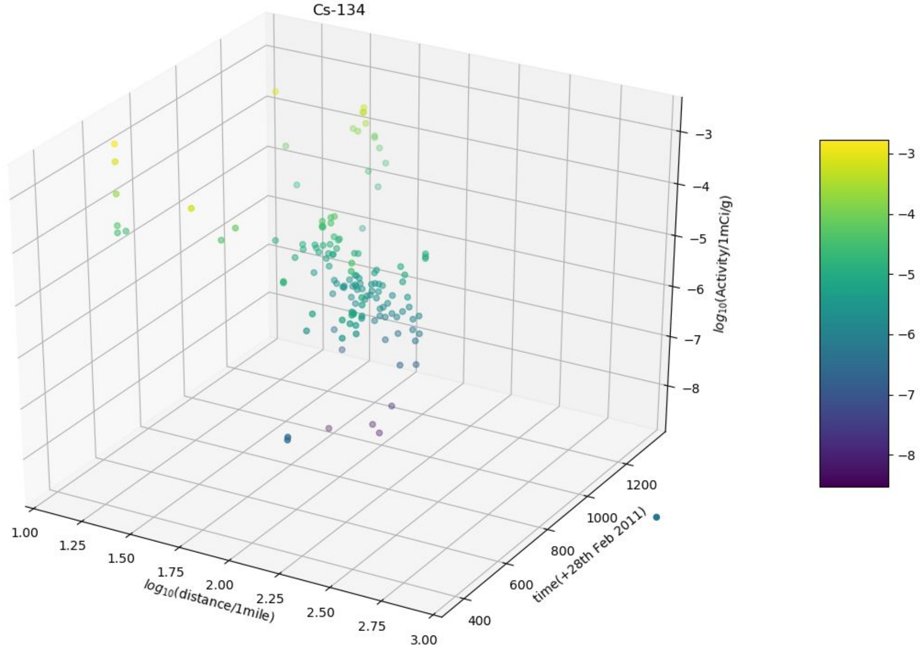






Radiation as a function of both distance and time





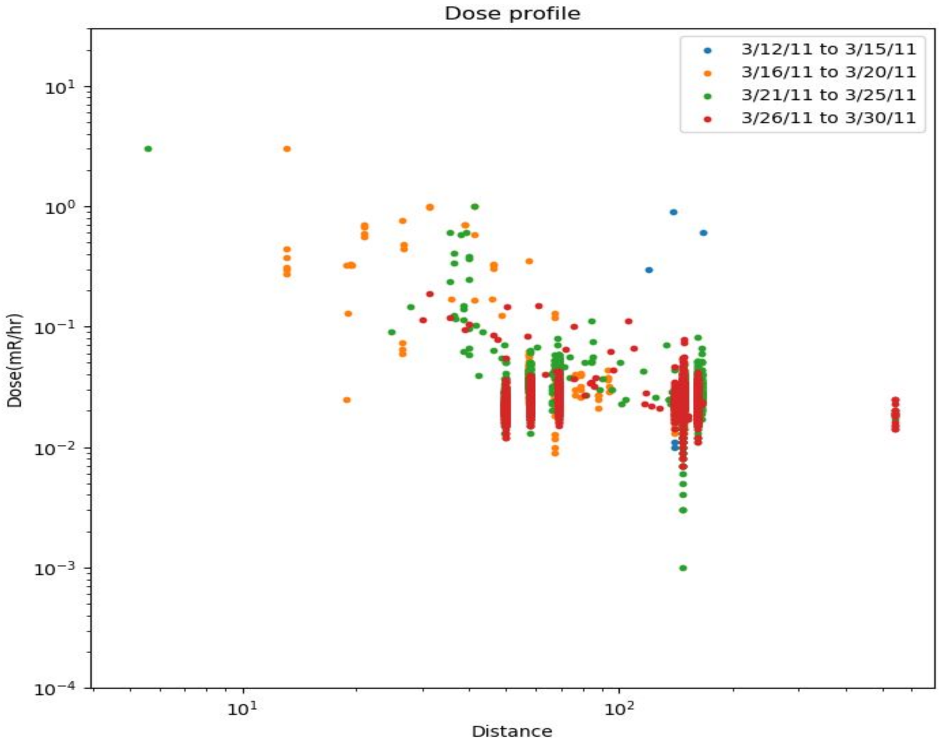
Impact on Non-Human Biota

- Animals, birds, marine life: Data from June 2011 (late phase of the accident)
- Terrestrial mammals and birds exposure was estimated at dose rates between 1.2 and 2.2 µGy/h in areas encompassing most of the range of ^{137}Cs deposition densities. (Approx 10x more than natural)
- 300 µGy/h have been estimated for soil-dwelling organisms in areas of high deposition density such as Okuma Town during the earlier intermediate phase.
- Effects on non-human biota in the marine environment would be confined to areas close to where highly radioactive water was released into the ocean.
- While higher than the benchmark level of 100 µGy/h, these dose rates are unlikely to have resulted in observable effects on populations and any effects would have been transient in nature.

Impact on Land, Infrastructure and Soil

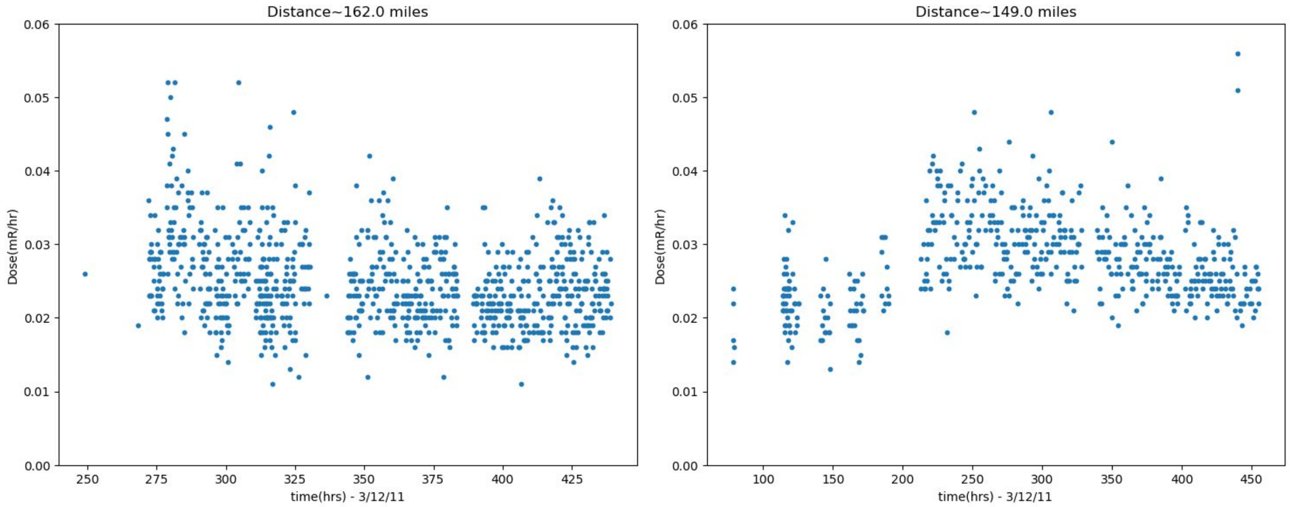
- After contamination plume passes, ground is main source of radiation.
- Dominant radionuclides: ^{137}Cs & ^{134}Cs (make the ground shine!)
- Deposition in soil took place predominantly in the NW direction.
- Combined Cs deposition was 1.8 x 107 Bq/m^2 near the plant and 1 x 106 Bq/m^2 about 20 kms from the plant in the same direction.
- Therefore, about 20 kms from the plant, the exposure is comparable to average background radiation in Japan (3.8 mSv/year), but higher than 1 mSv/year exposure limit for the public.

Dose Profiles from Real Data



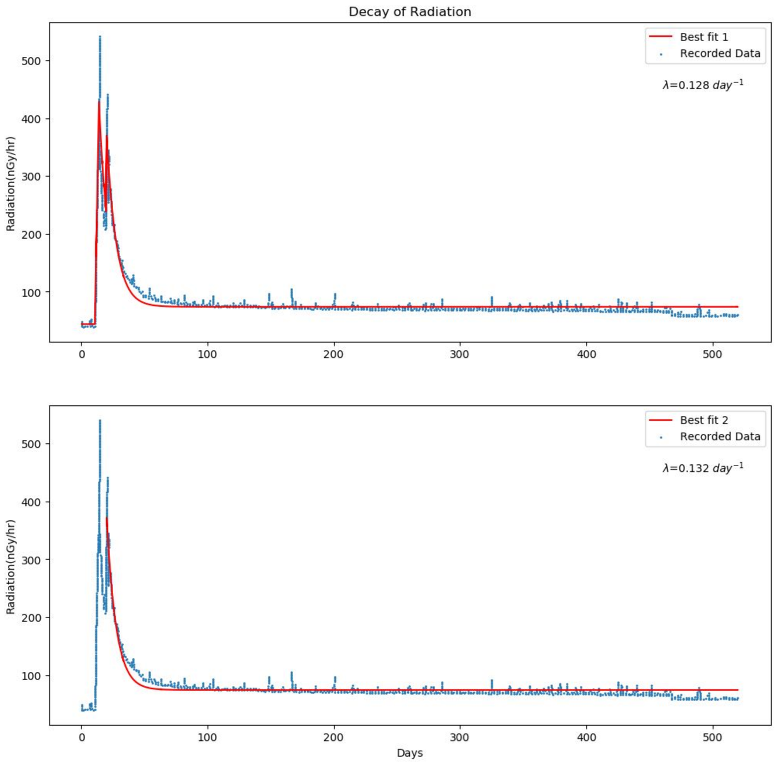
Overall dose profile

Dose Profile from Real Data



- This figure has something specific to Fukushima Explosions
- No exponential decay
- We see a small bump in the dose at around 220 hrs
- Approximately 4 days from the first reading
- Time between the two explosions?

Dose Profile from Real Data



- Data taken 111km from Fukushima
- Clear exponential decay visible
- Can clearly identify 2 different peaks corresponding to 2 explosions
- Fit an exponential decay curve to this data
- Closely matches decay constant of I-131

Impact on Air and Water Supply

- Main radionuclides - I-131 (half life 8 days) and Cs-137 (half life 30 years).
- Cs-137 is easily carried and can contaminate land for some time.
- Cs-134 (half life 2 years) is also produced in small amounts and can be taken into body because of its soluble nature, but it is not lethal.
- Most of the Cs-137 produced was released into the ocean.
- While most of I-131 was present in the atmosphere.
- I-131 had the most radioactivity because of its lower half life.
- Dose commitment from breathing is around 1.5e-8 Sv/Bq for I-131.
- Uncertainties are large for dose commitment because of the presence of other radioactive nuclides.

Impact on Food Supply

- Early measurements showed more than provisional regulation values of concentration of I-131 in vegetables in affected areas.
- 3.3% of food from Fukushima region had above limit contamination.
- Arrangements were made for controlling food and drinking water.
- Levels of radioactive Iodine decreased significantly during the first few weeks because of low half life.
- Provisional regulations were added for activity concentrations of radioactive Iodine in fishery products.
- In 2012, Japanese standard for Cs was dropped from 500 to 100 Bq/kg.
- Only 0.6% fishes caught off shore exceeded this lower limit in 2014 when compared to 53% in months following the disaster.

Thank you!